Microwave Photonic Applications of Semiconductor Laser Nonlinear Dynamics

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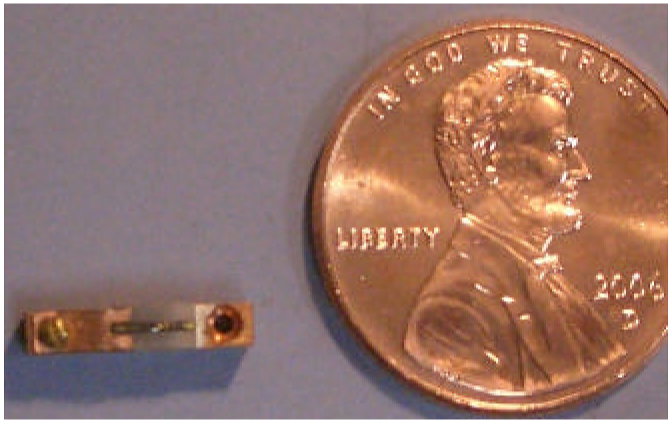
Outline

- Introduction
  - Semiconductor laser nonlinear dynamics
  - Feasibility for photonic microwave applications
- Optical Injection Period-One Oscillation
  - Photonic microwave properties
  - Applications: Generation of stable photonic microwave
    - Lidar detection
    - Radio-over-fiber source
    - AM-to-FM converter
- Optical Injection Period-Two Oscillation
  - Generation of period-two state
  - Application: All-optical microwave frequency converter
- Optoelectronic Feedback Frequency-Locking
  - Generation of frequency-locking state
  - Application: Photonic microwave comb generation
- Summary

Introduction

- Since the invention of laser in 1960, different kinds of laser media were developed, including:
  - gases, liquids, solid-state crystals, and semiconductors

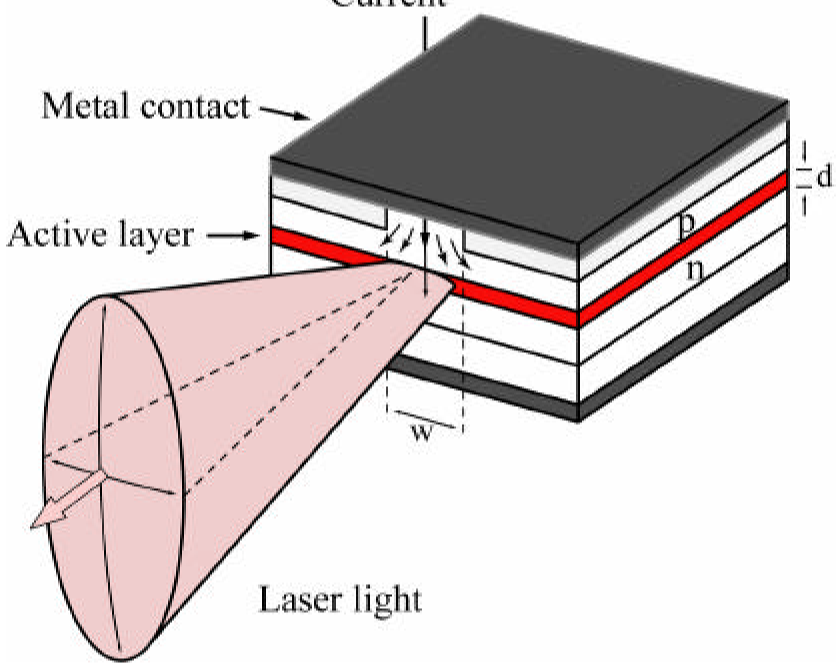
- Semiconductor lasers (or laser diodes) are compact, fast, and mass producible
  - Applications: optical communication, data storage, pump source for other lasers

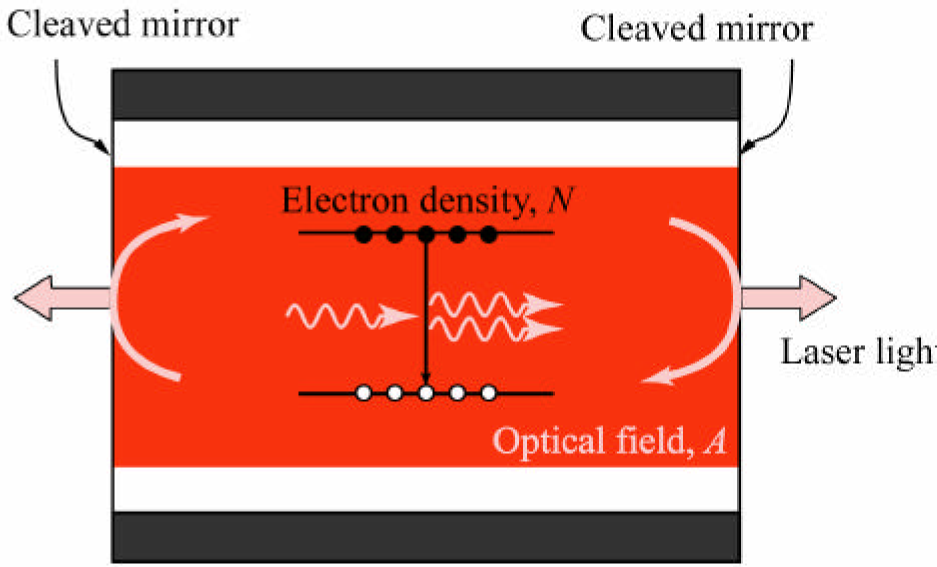


- Nonlinear dynamics of semiconductor lasers have attracted much attention over the last decade
  - Emerging applications:
    - Chaos communication – high complexity for secure communication
    - Chaos control – methods to avoid nonlinear dynamics

How about the other dynamics? Are they useful?

Semiconductor Laser

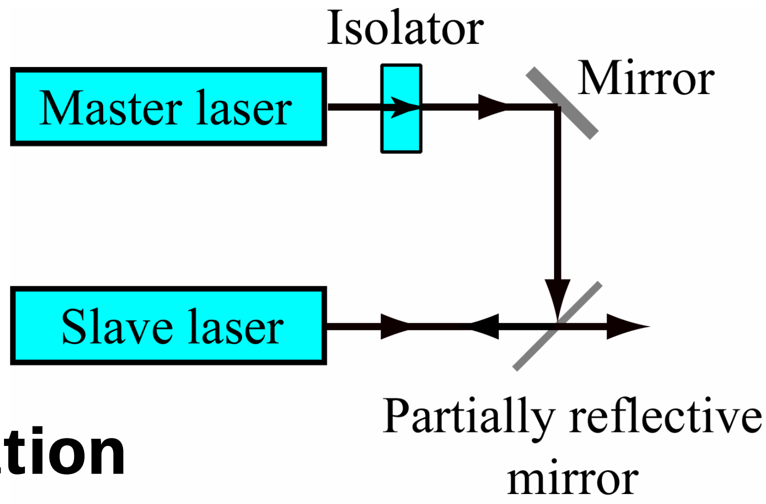




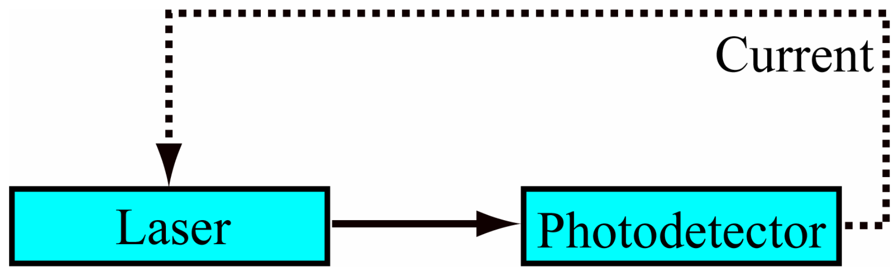
- Dynamics are governed by two nonlinearly coupled rate equations in terms of:
  - the optical field A
  - the charge-carrier density N
- Typical modulation bandwidth ~ 10 GHz
- This allows **nonlinear dynamics** in **microwave** domain

Perturbation Systems

- **Solitary** semiconductor laser emits continuous-wave (CW) light, we need to invoke the nonlinear dynamics through different perturbations.



- **Optical injection: oscillation**
  - period-one oscillation (P1)
  - period-two oscillation (P2)
  - chaotic oscillation
- **Optoelectronic feedback: pulsation**
  - regular pulsing
  - frequency-locked pulsing
  - quasi-periodic pulsing
  - chaotic pulsing



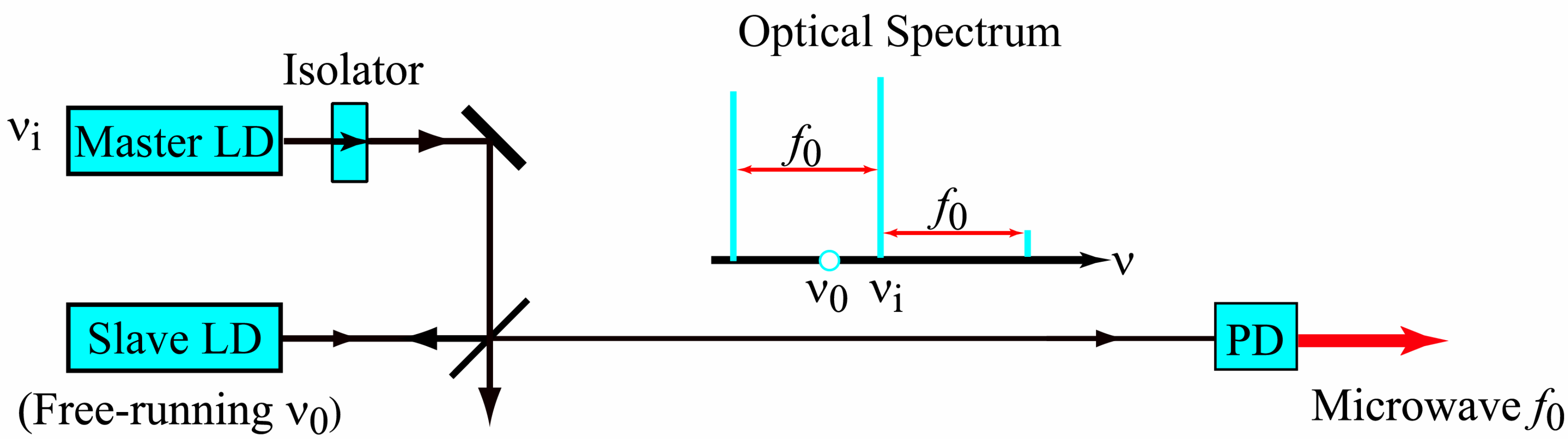
Semiconductor laser nonlinear dynamics can be applied for photonic microwave applications.

Optical Injection Period-One State

- Photonic microwave characteristics
- Applications

Optical Injection System

- We control an optically injected laser diode to result in the period-one (P1) state for **photonic microwave generation**

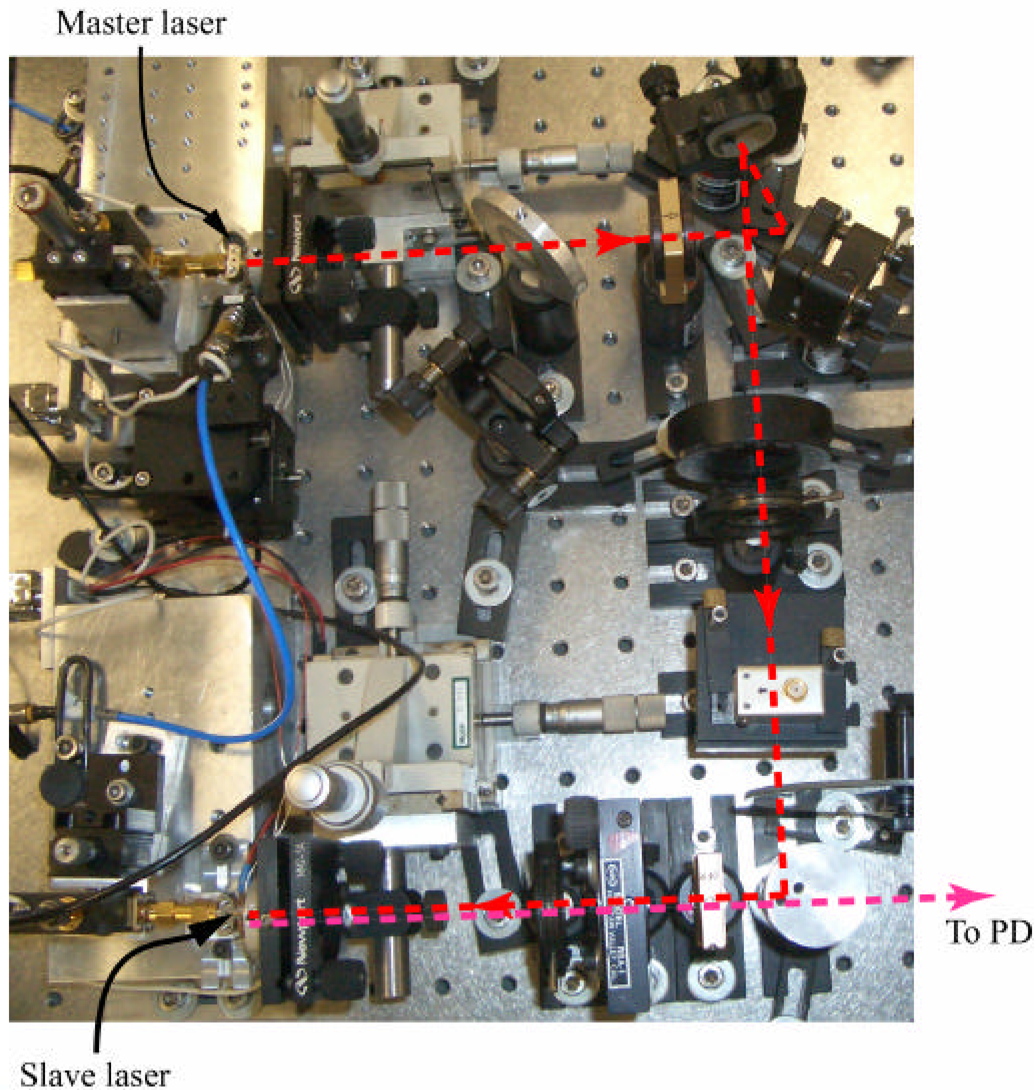


- As injection strength increases:
  - Master injection-locks the slave to ν_i
  - Hopf bifurcation into P1 state
    (Equivalent to undamping the relaxation between electrons and photons)
  - Light is converted into microwave f_0 by a PD

Experiment

- Distributed feedback (DFB) single-mode semiconductor laser

Wavelength	1.3 μm
Threshold	18 mA
Bias current	40 mA
Power	4.5 mW
Relaxation Resonance f_r	10 GHz

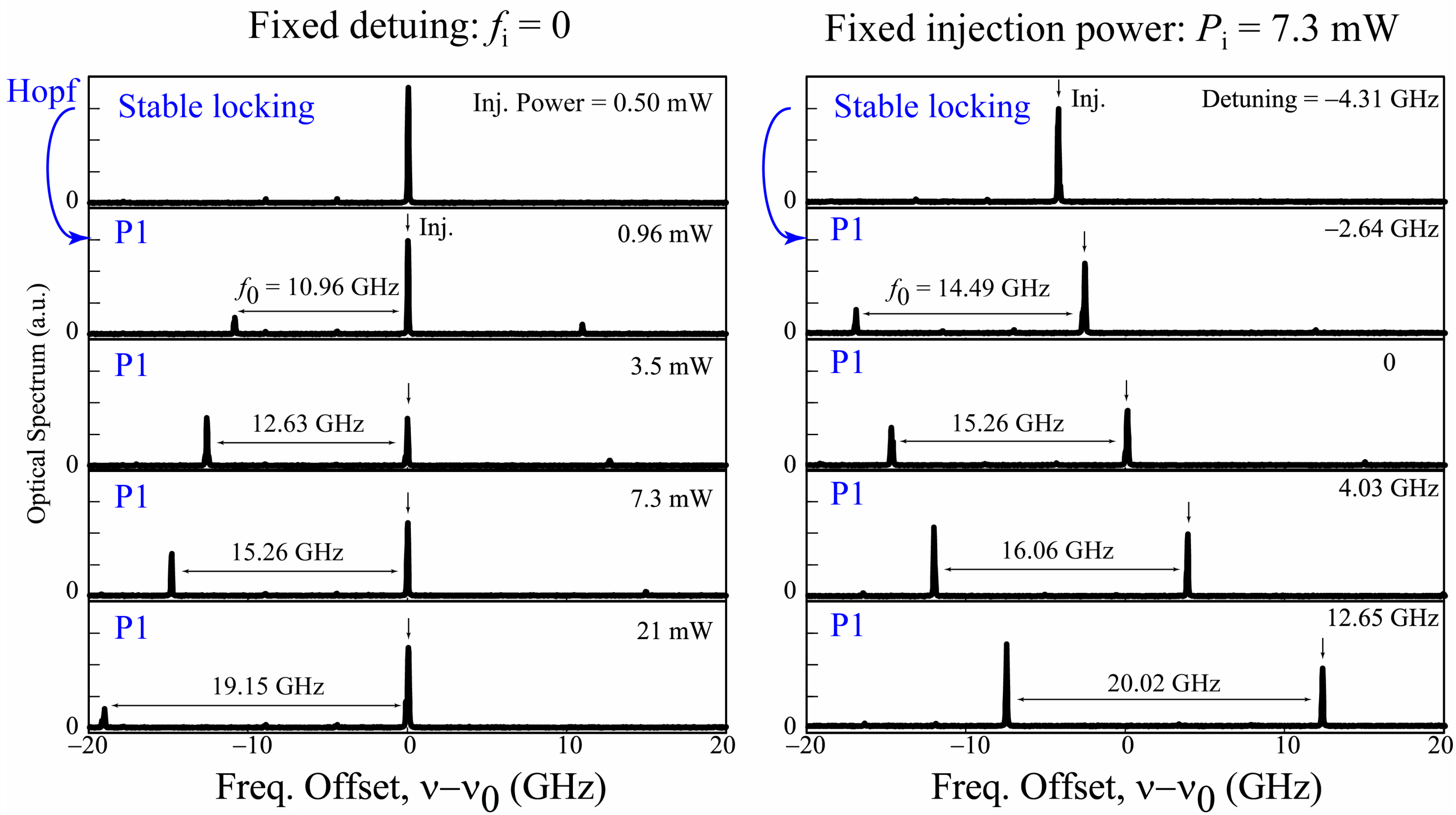


- Injection parameters:

Strength	$\xi_i \propto P_i^{1/2}$
Detuning	$f_i = n_i - n_0$

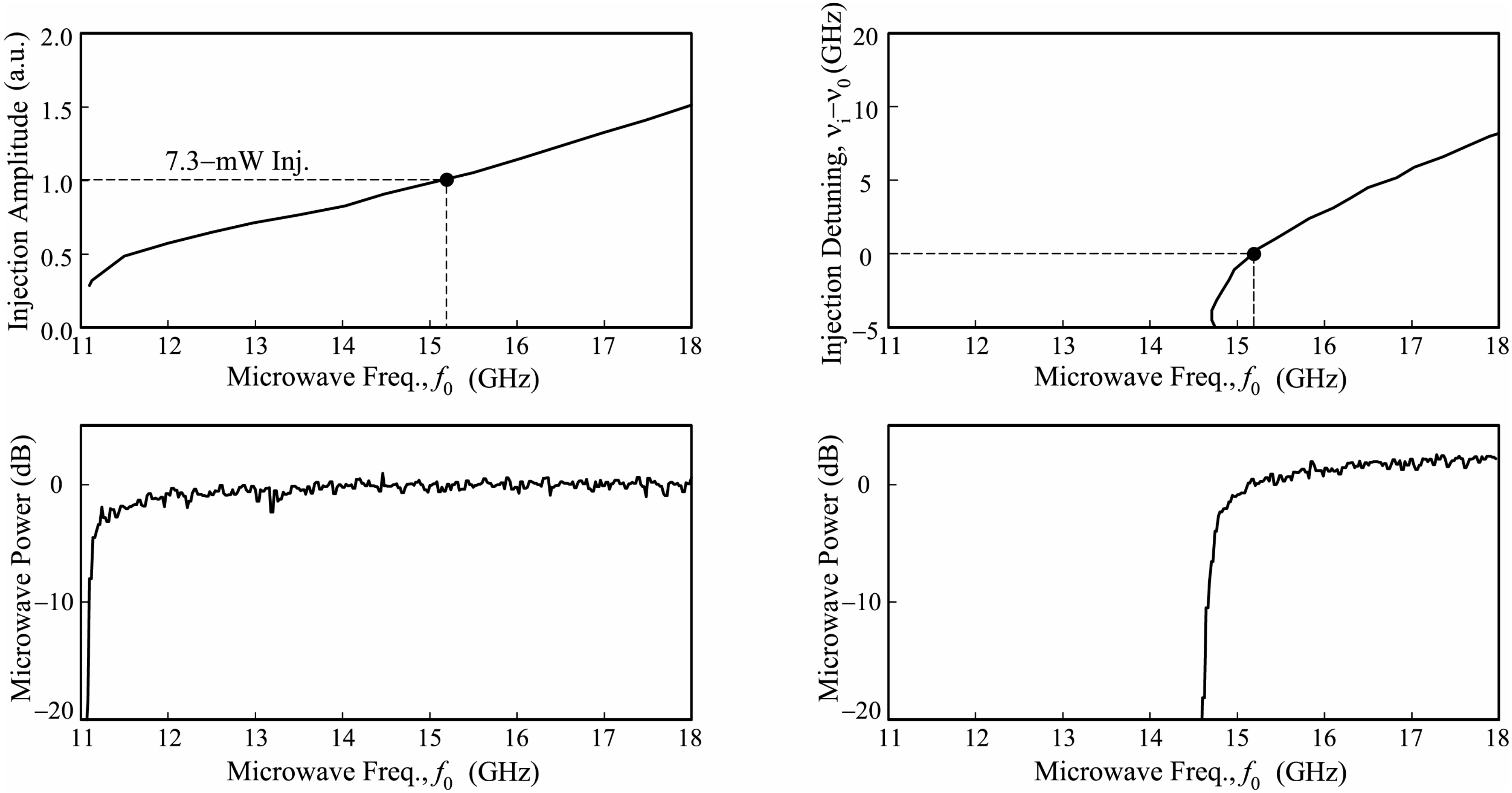
P1 Spectrum

- P1 microwave frequency f_0 increases with both ξ_i and f_i.



Tuning Characteristics

- P1 microwave frequency f_0 increases with both injection strength and detuning.



Simulation Model

- Rate equations

Optical field / Cold cavity / Gain medium / Optical injection:

$$\frac{d}{dt}A = \left[-\frac{\gamma_c}{2} + i(\omega_0 - \omega_c)\right]A + \frac{\Gamma}{2}(1 - ib)gA + \eta A_i e^{-i2\pi f_i t}$$

Electron density / Pump / Spontaneous decay / Stimulated decay:

$$\frac{d}{dt}N = \frac{J}{ed} - \gamma_s N - g\frac{2n_c^2\epsilon_0}{\hbar\omega_0}|A|^2$$

where

Gain $g = g_0 + \gamma_n \frac{N - N_0}{S_0} - \gamma_p \frac{S - S_0}{\Gamma S_0}$

Photon density $S = \frac{2n_c^2\epsilon_0}{\hbar\omega_0}|A|^2$

Cavity decay rate γ_c	5.36×10^{11} (s^{-1})
Spontaneous carrier relaxation rate γ_s	5.96×10^{9} (s^{-1})
Differential carrier relaxation rate γ_n	7.53×10^{9} (s^{-1})
Nonlinear carrier relaxation rate γ_p	1.91×10^{10} (s^{-1})
Linewidth enhancement factor b	3.2

Normalized Rate Equations

- Runge-Kutta integration is performed on the normalized rate equations:

$$\frac{\mathrm{d}a_\mathrm{r}}{\mathrm{d}t} = \frac{1}{2}[\frac{\gamma_\mathrm{c}\gamma_\mathrm{n}}{\gamma_\mathrm{s}\tilde{J}}\tilde{n} - \gamma_\mathrm{p}(a_\mathrm{r}^2 + a_\mathrm{i}^2 - 1)](a_\mathrm{r} + ba_\mathrm{i}) + \xi_\mathrm{i}\gamma_\mathrm{c}\cos\Omega_\mathrm{i}t$$

$$\frac{\mathrm{d}a_\mathrm{i}}{\mathrm{d}t} = \frac{1}{2}[\frac{\gamma_\mathrm{c}\gamma_\mathrm{n}}{\gamma_\mathrm{s}\tilde{J}}\tilde{n} - \gamma_\mathrm{p}(a_\mathrm{r}^2 + a_\mathrm{i}^2 - 1)](-ba_\mathrm{r} + \mathrm{i}a_\mathrm{i}) - \xi_\mathrm{i}\gamma_\mathrm{c}\sin\Omega_\mathrm{i}t$$

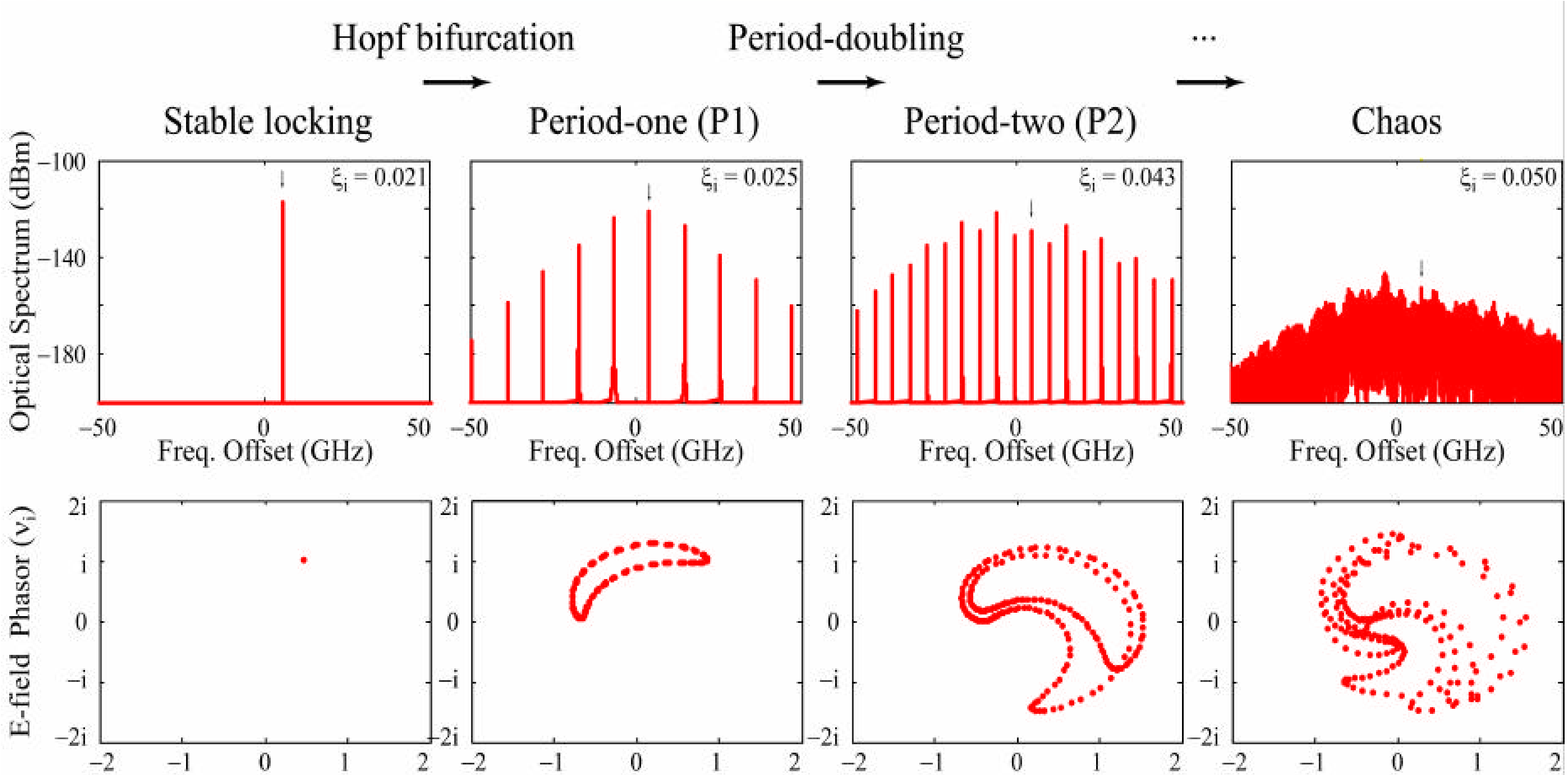
$$\frac{\mathrm{d}\tilde{n}}{\mathrm{d}t} = -[\gamma_\mathrm{s} + \gamma_\mathrm{n}(a_\mathrm{r}^2 + a_\mathrm{i}^2)]\tilde{n} - \gamma_\mathrm{s}\tilde{J}(a_\mathrm{r}^2 + a_\mathrm{i}^2 - 1) + \frac{\gamma_\mathrm{s}\gamma_\mathrm{p}}{\gamma_\mathrm{c}}\tilde{J}(a_\mathrm{r}^2 + a_\mathrm{i}^2)(a_\mathrm{r}^2 + a_\mathrm{i}^2 - 1)$$

where

$$a_\mathrm{r} + \mathrm{i}a_\mathrm{i} = A/|A_0| \qquad 1 + \tilde{n} = N/N_0$$

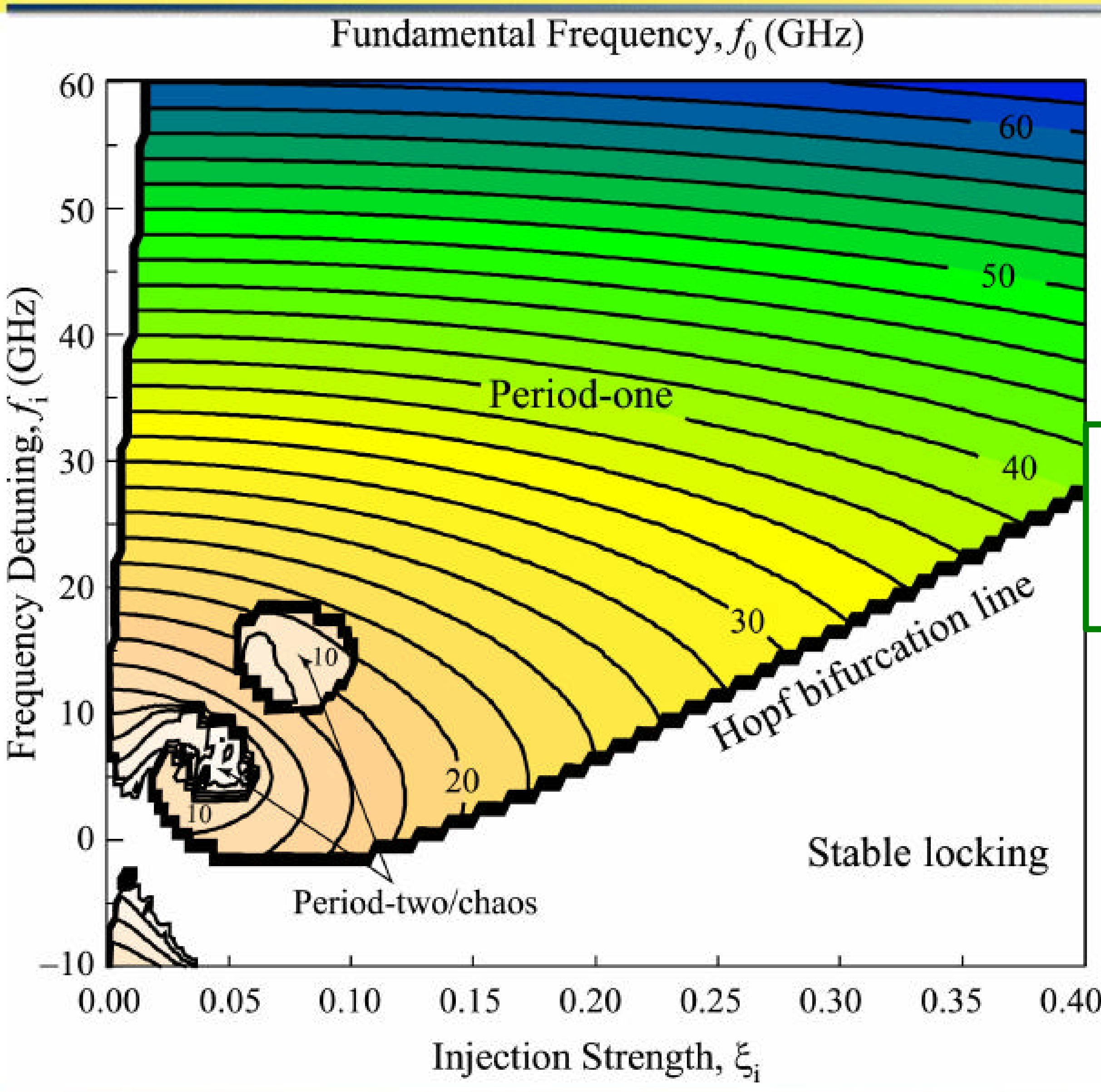
$$\xi_\mathrm{i} = \eta|A_\mathrm{i}|/\gamma_\mathrm{c}|A_0| \qquad \tilde{J} = (J/ed - \gamma_\mathrm{s}N_0)/\gamma_\mathrm{s}N_0$$

Nonlinear Dynamics



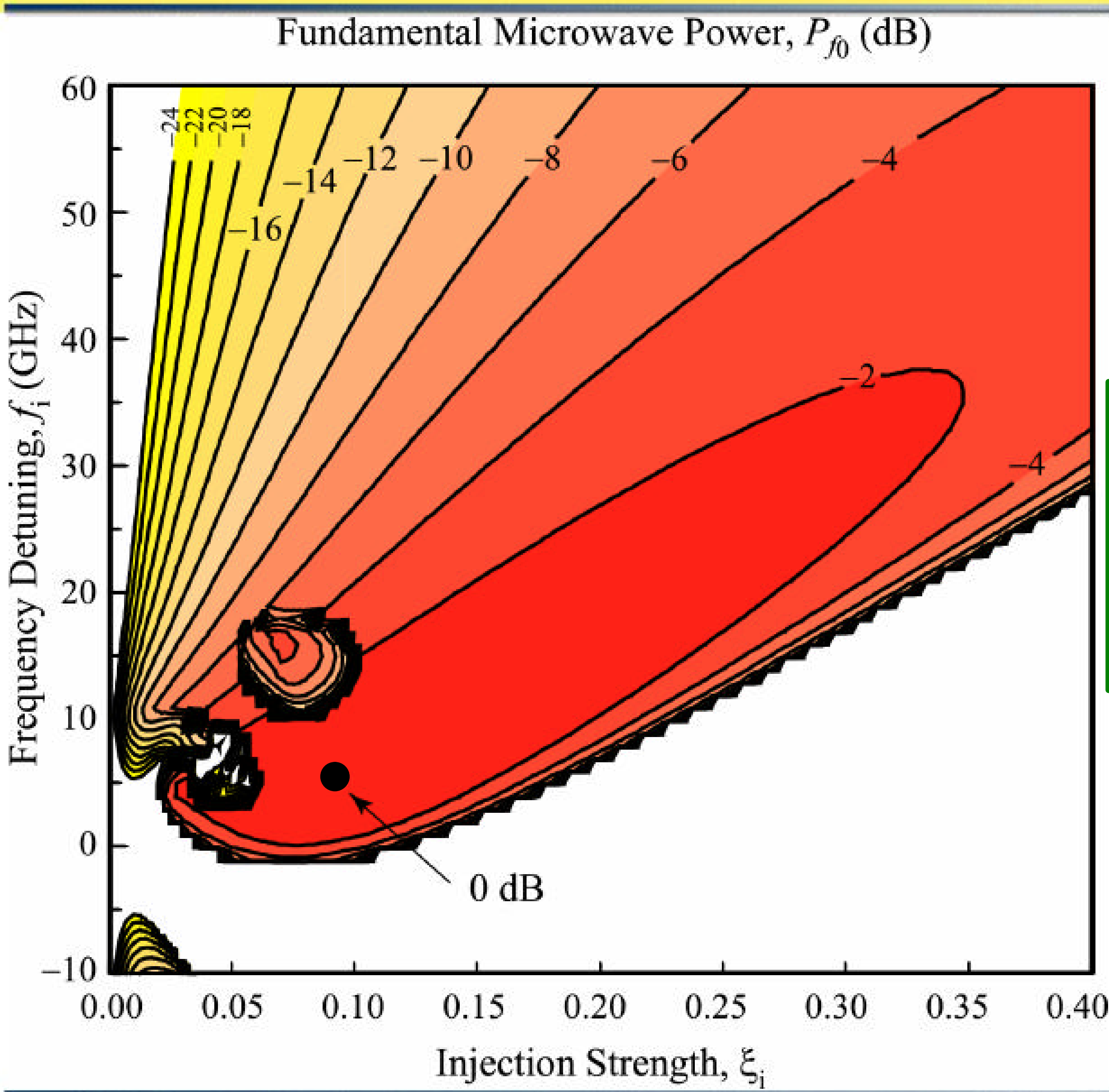
- The P1 state is part of the nonlinear dynamics.

Map of Microwave Frequency



Microwave frequency of 6 times the relaxation resonance is generated.

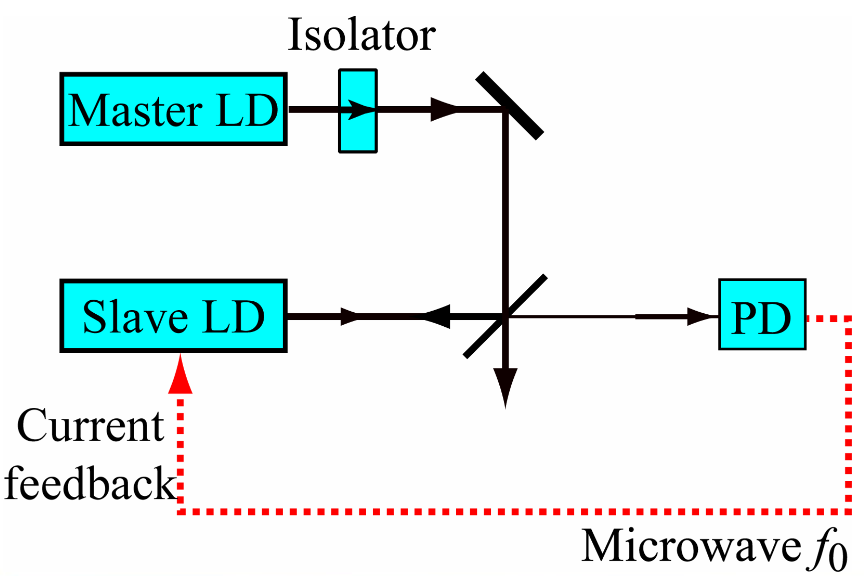
Map of Microwave Power

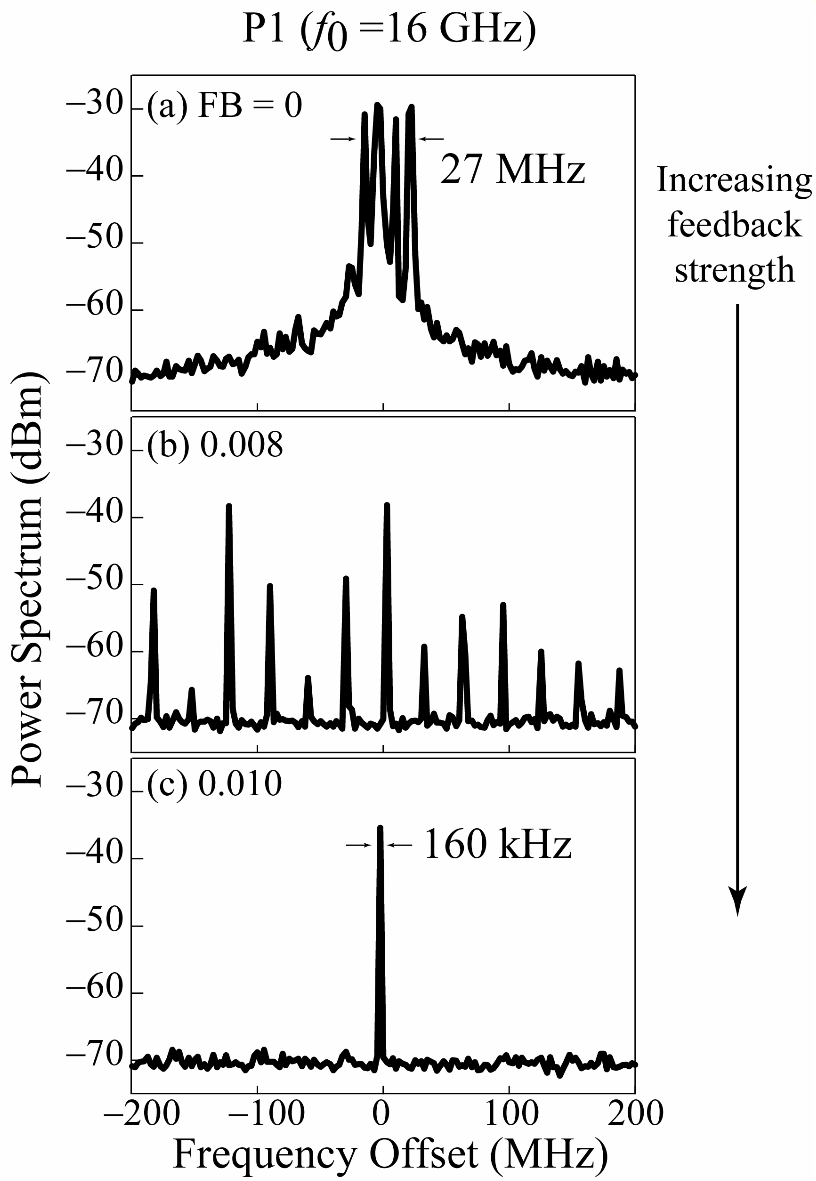


Microwave power is the strongest when the injection detuning is slightly above the Hopf bifurcation line.

Microwave Feedback

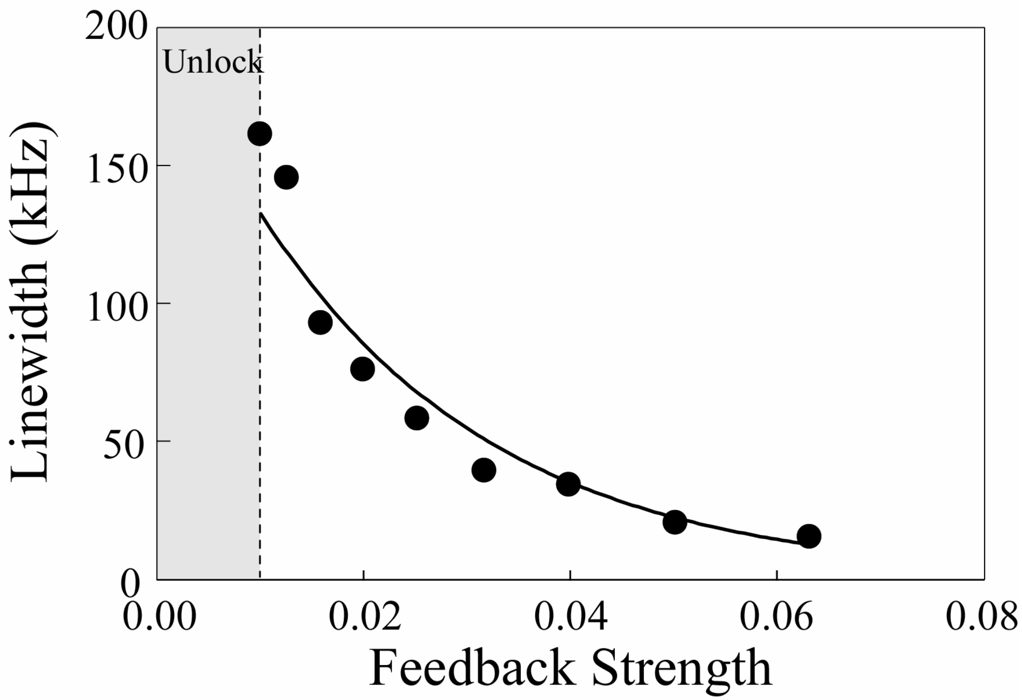
- Spontaneous emission noise and injection fluctuation cause a microwave linewidth.
- Significant linewidth reduction by a weak optoelectronic feedback.

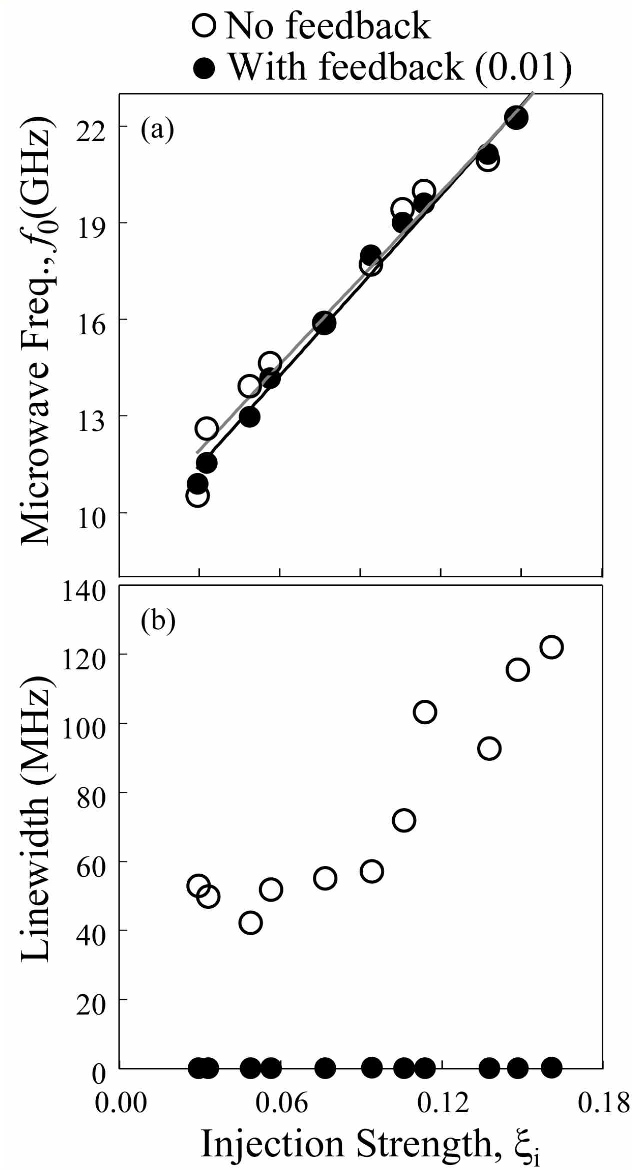




Linewidth Reduction

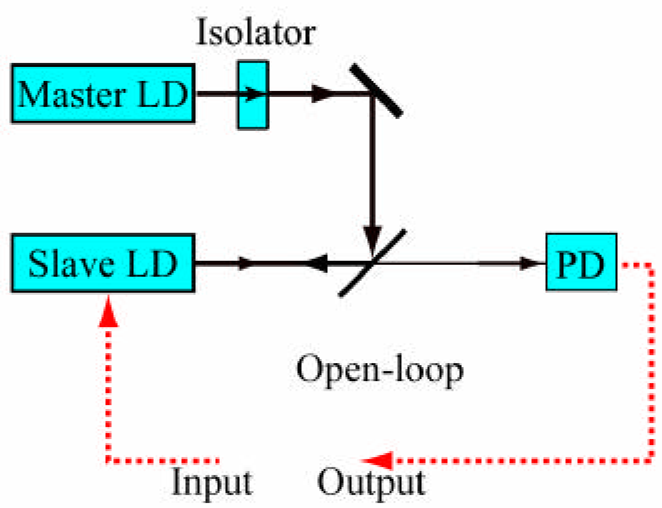
- Linewidth reduces as the feedback strength increases.

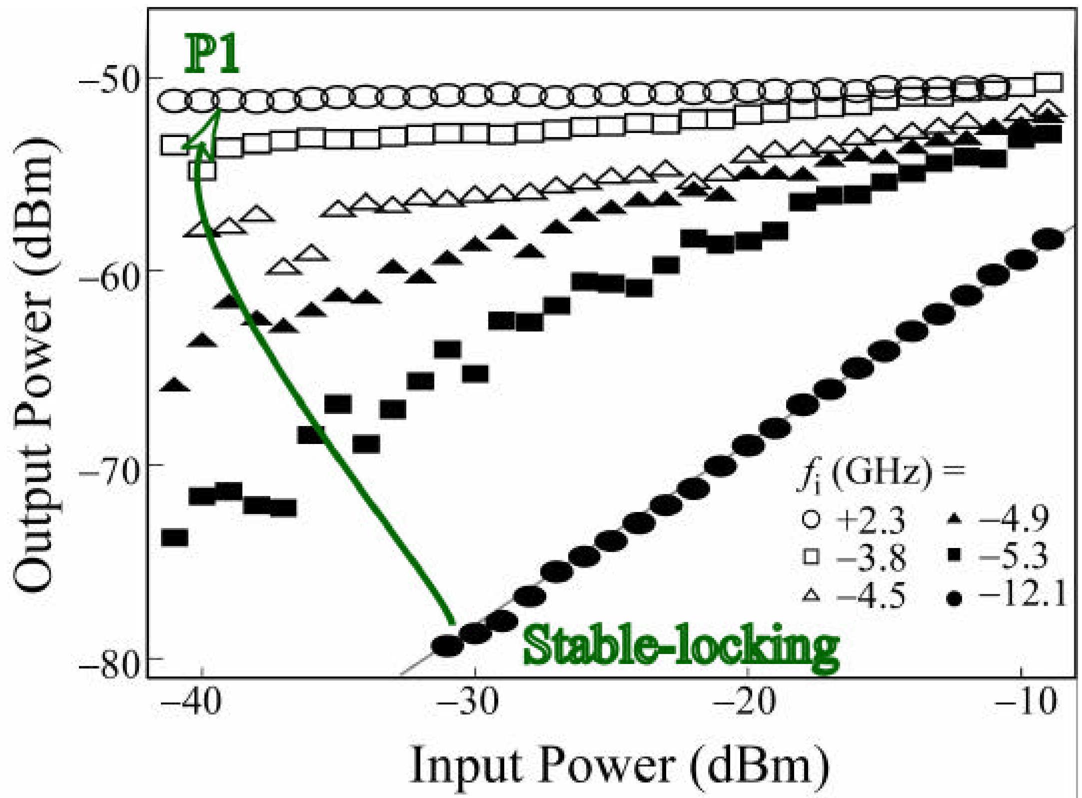




P1 dynamics generate stable photonic microwave without using a bulky electronic microwave generator.

Mechanism

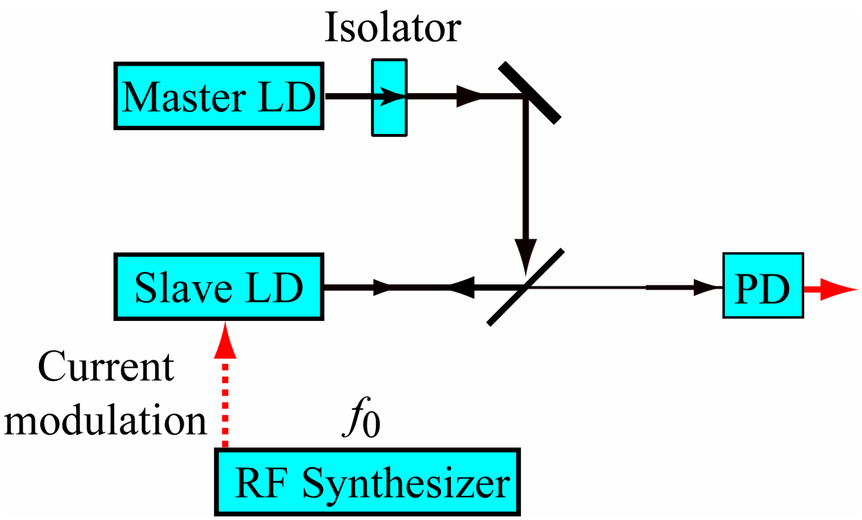


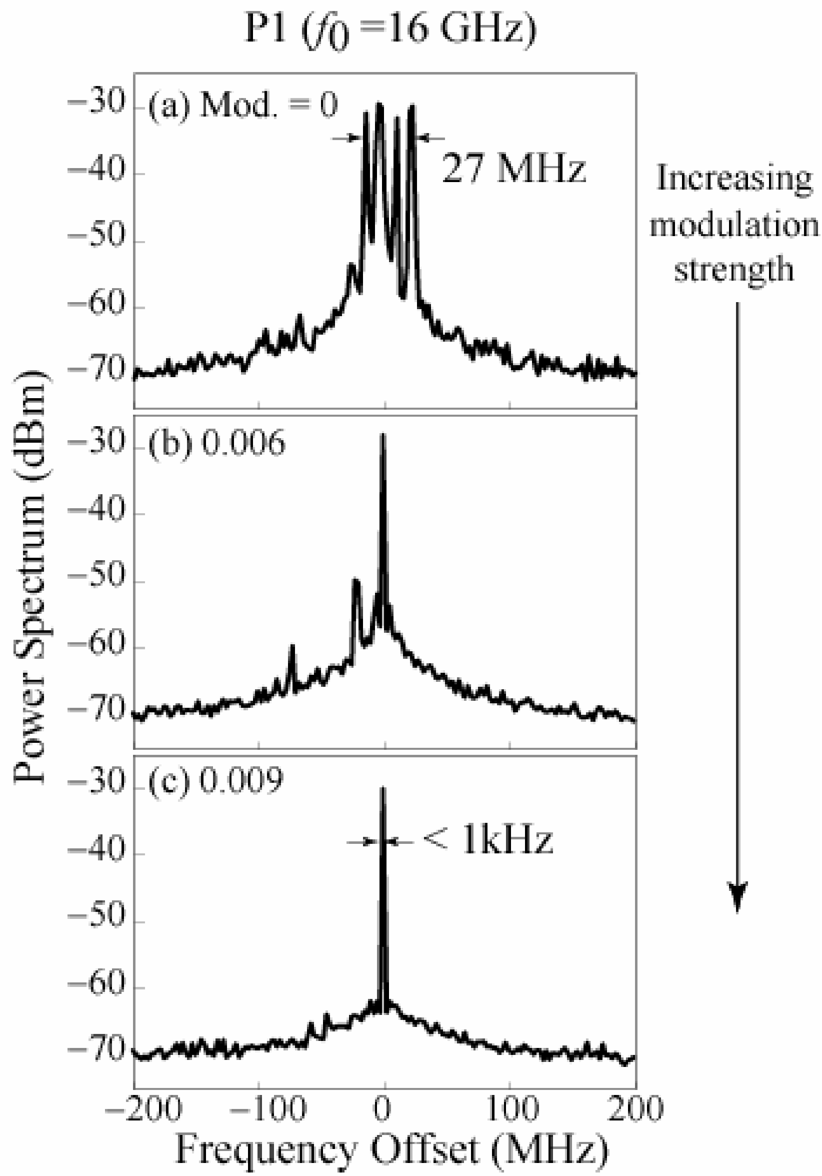


- Open-loop microwave gain is saturated by the P1 oscillation even before the feedback is applied.
- Linewidth narrowing is due to *self-injection locking*, rather than the onset of optoelectronic oscillation.

Microwave Injection-Locking

- Further linewidth reduction by a weak and stable microwave injection at f_0 .

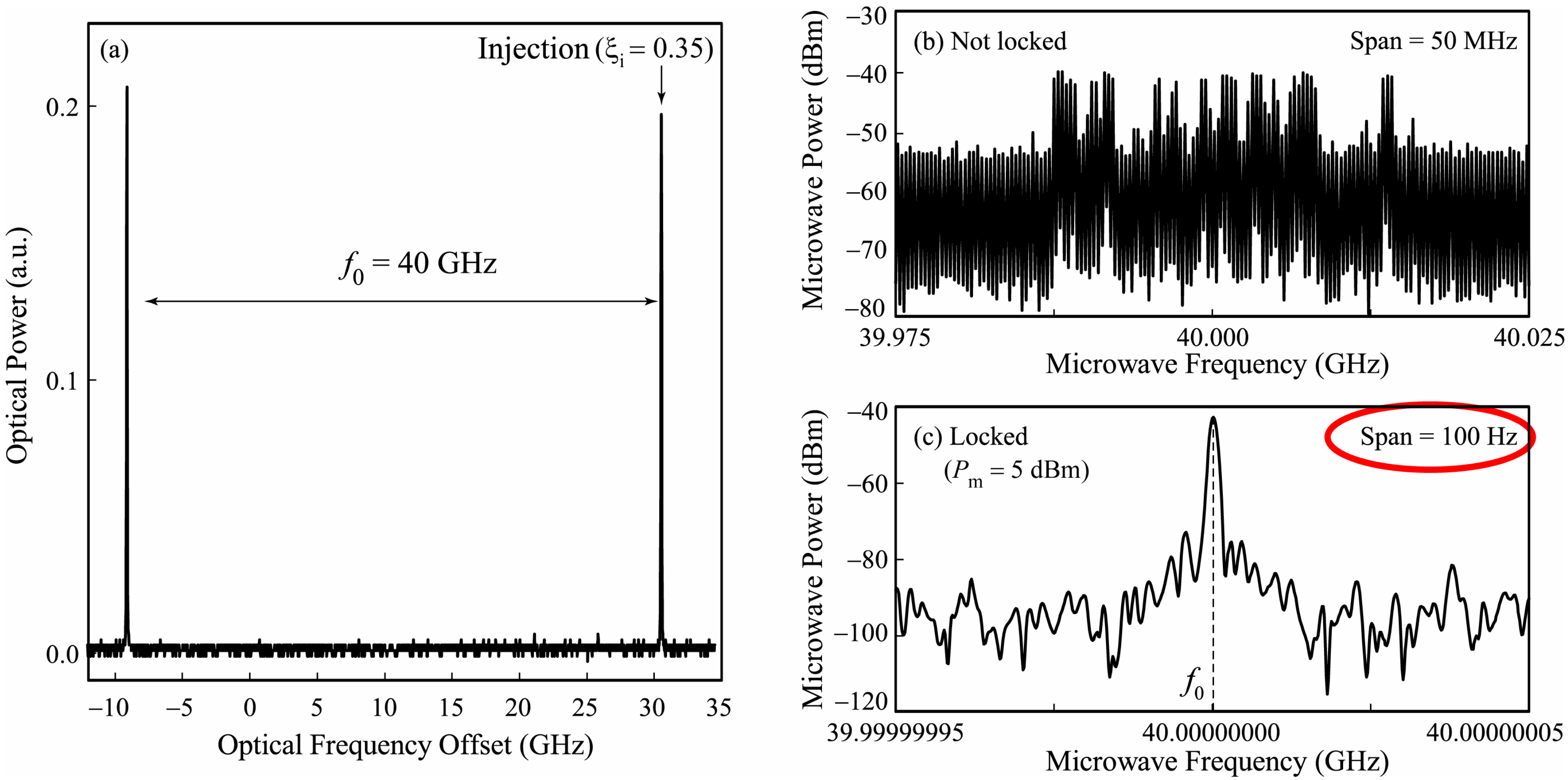




Subharmonic Locking

- Locking by injection at subharmonic frequencies

e.g. 40 GHz P1 is locked by 20 GHz modulation



Comparison of Photonic Microwave Sources

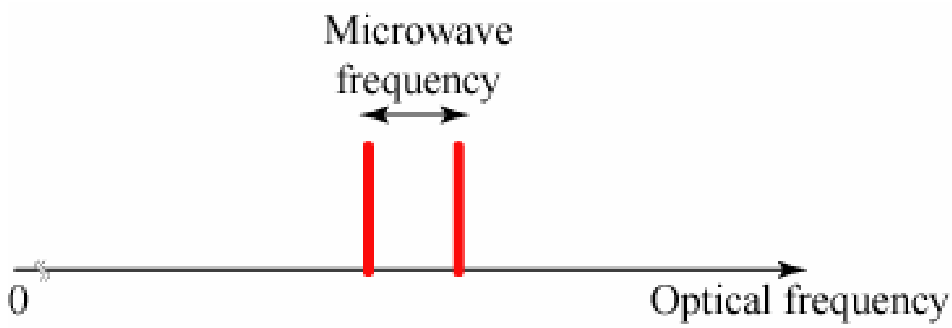
	Tunability	Stability	Optical Loss	Electronics	Single-sideband
Direct mod.	Limited	Good	No loss	Simple	No
Self-pulsation	Poor	Good	No loss	Simple	No
Modelock	Poor	Good	Lossy	Simple	Yes
Heterodyne	Good	Poor	No loss	Simple	Yes
Optical PLL	Good	Good	No loss	Complicated	Yes
Dual-mode	Good	Poor	No loss	Complicated	Yes
EOM	Good	Good	Lossy	Moderate	Require design
EAM	Good	Good	Lossy	Moderate	Require design
Period-one dynamics	**Good**	**Good**	**No loss**	**Simple**	**Yes**

Optical Injection Period-One State

- Photonic microwave characteristics
- Applications

Applications of the P1 State

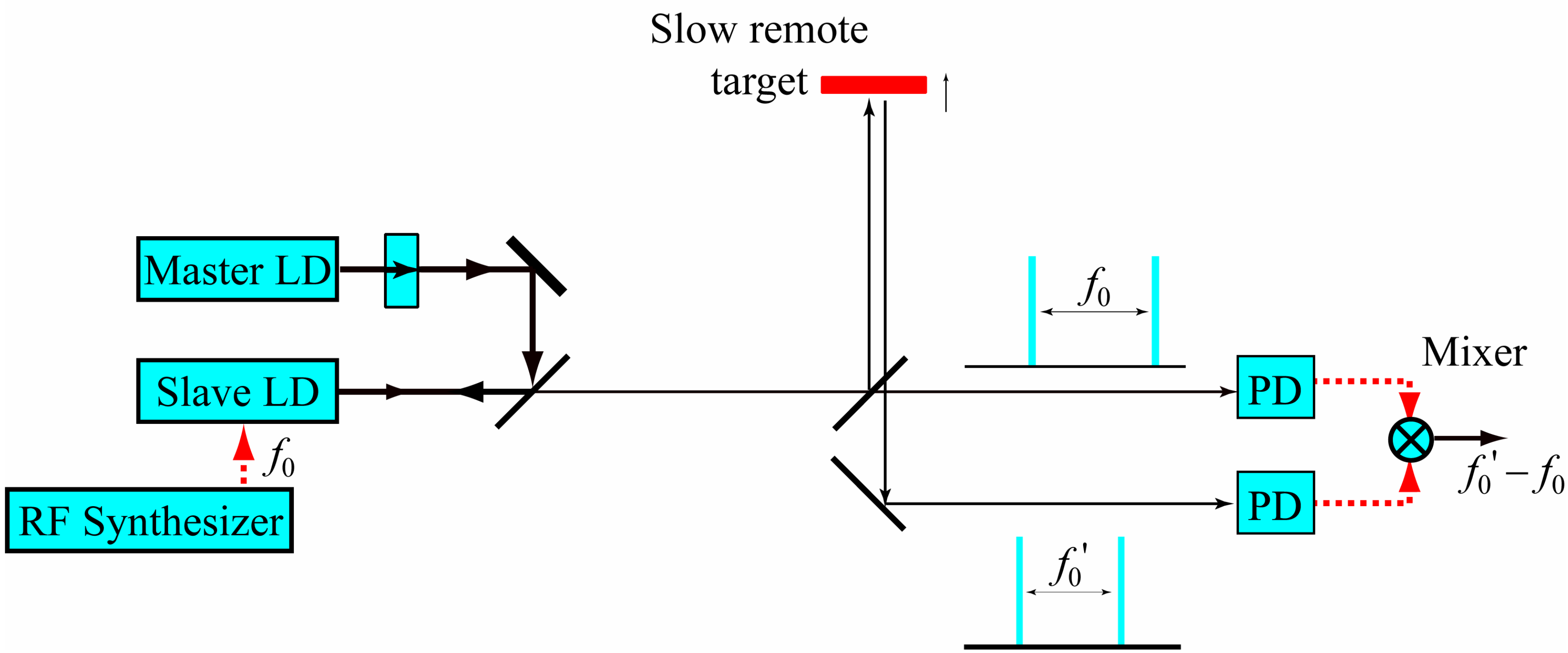
- P1 photonic microwave generation:



Property	Application
Easily stabilized	Doppler lidar
SSB optical spectrum	Radio-over-fiber transmission
Tunable optically	AM-to-FM conversion

Application 1: Doppler Lidar

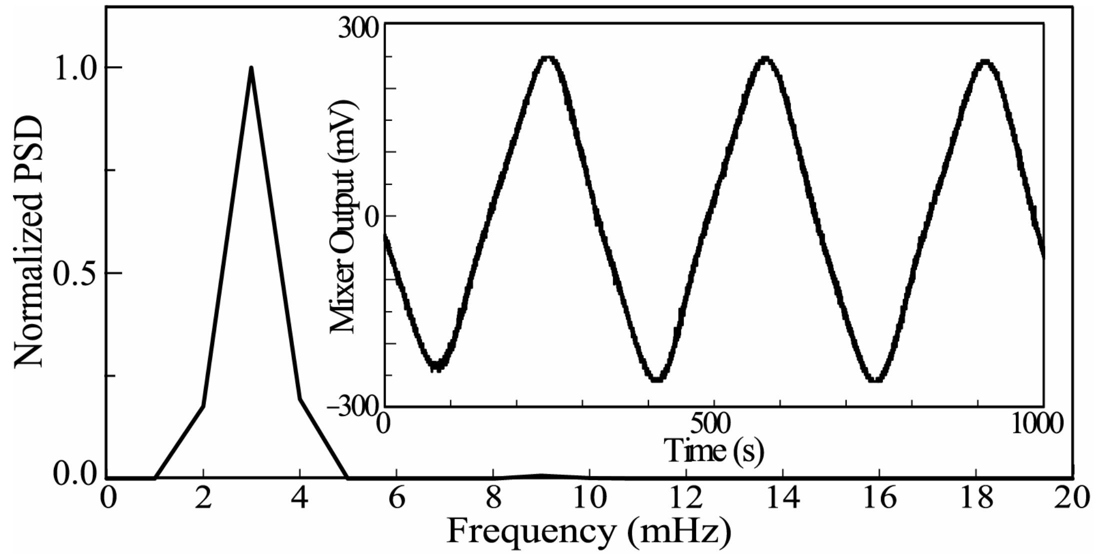
- Doppler lidar (light detection and ranging)

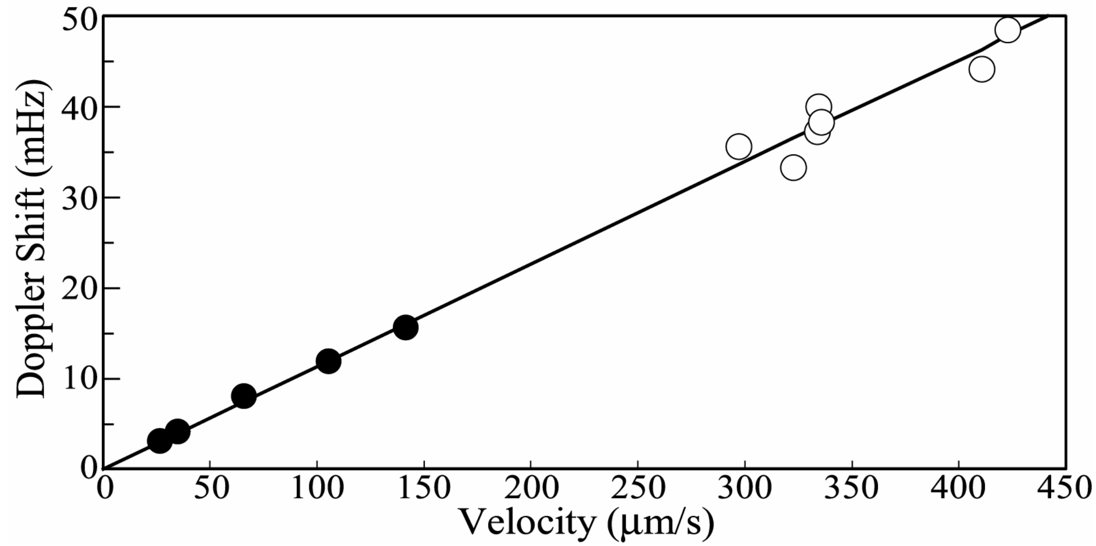


- Uses the stable microwave to optically detect an extremely slow target.

Velocity Measurement

- This method relies on coherently mixing the microwave signals, but the optical linewidth is not important.
- For a stable microwave linewidth < 1 kHz, the allowed target distance > 24 km.

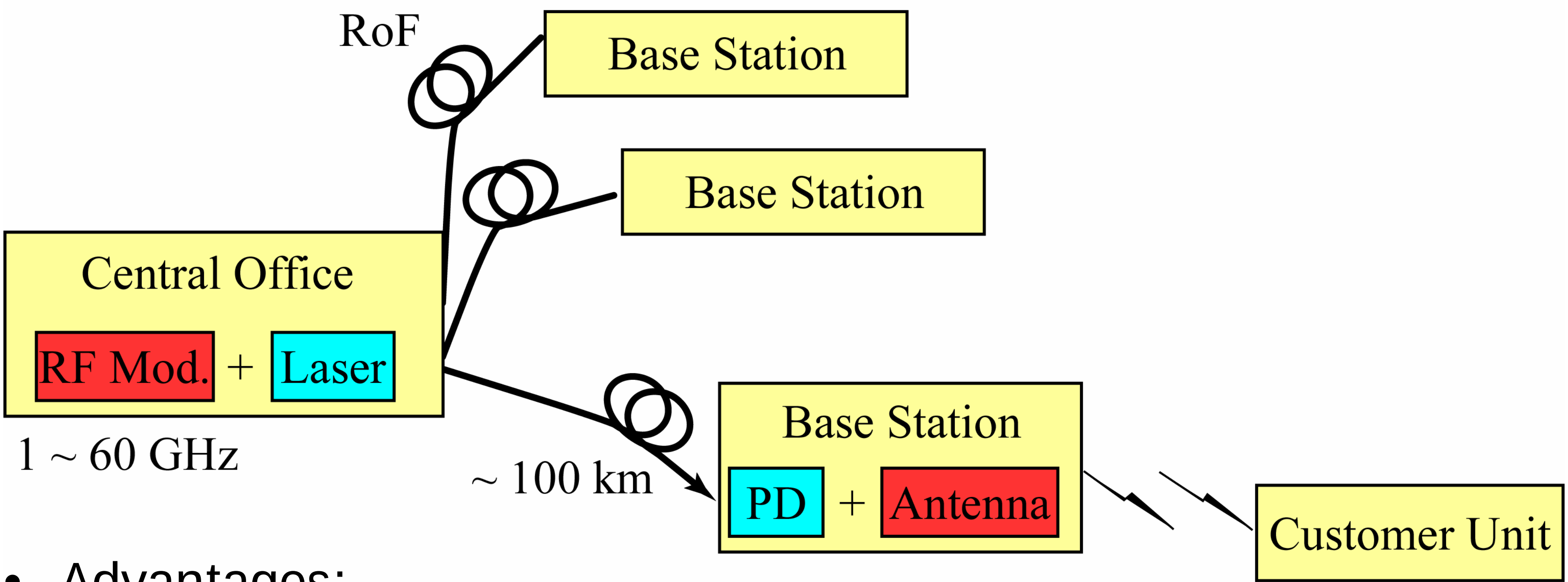




Using a 17 GHz P1, we measured target velocity of 26 µm/s located 8 km away

Application 2: Radio-over-Fiber

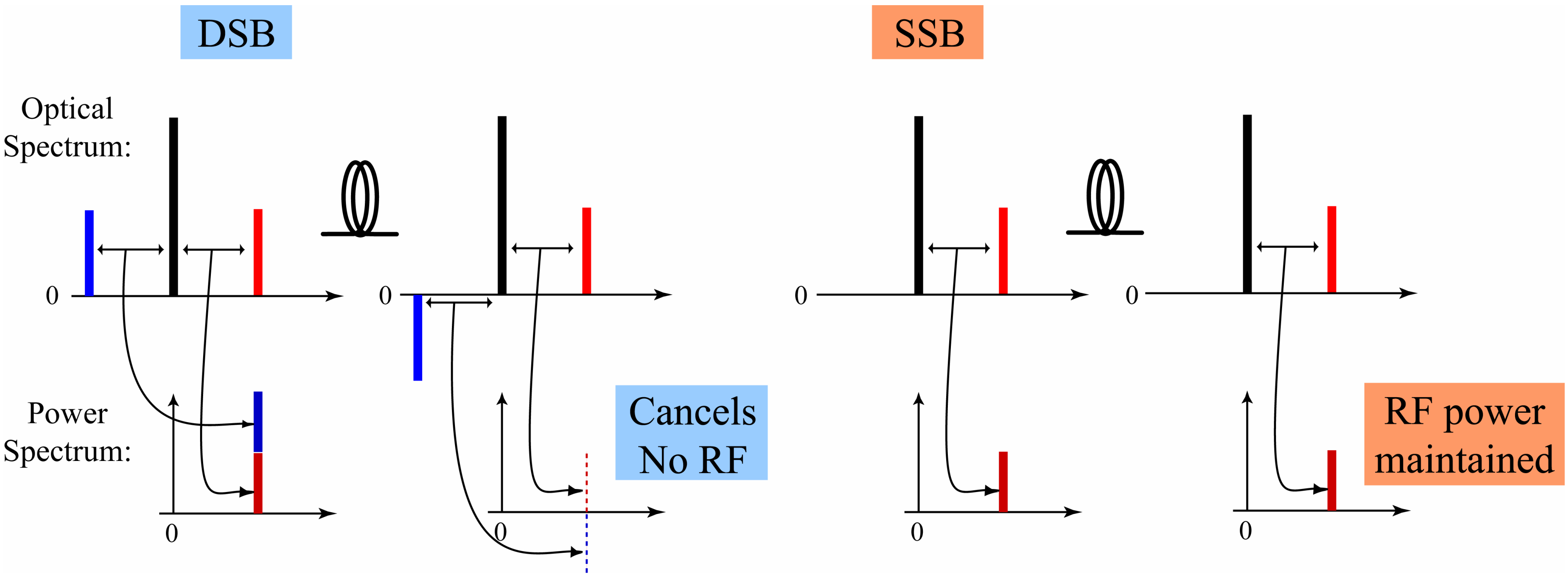
- Radio-over-fiber (RoF) system:



- Advantages:
  - Centralization of electronics
  - Simple base station design
  - Long distance distribution of microwave
  - Increased coverage and cell density

Dispersion-Induced Power Penalty

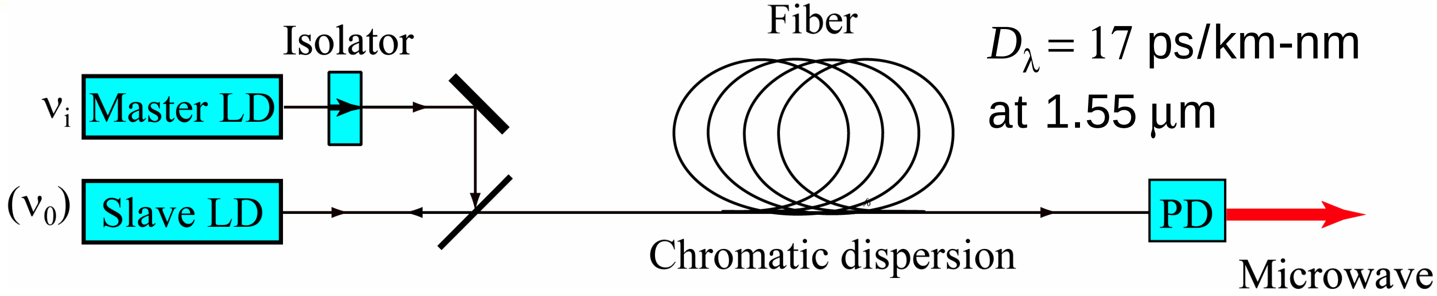
- Because of chromatic dispersion in optical fibers:
  - Double-sideband (DSB) signal may suffer RF power penalty.
  - Single-sideband (SSB) signal is immune to power penalty.

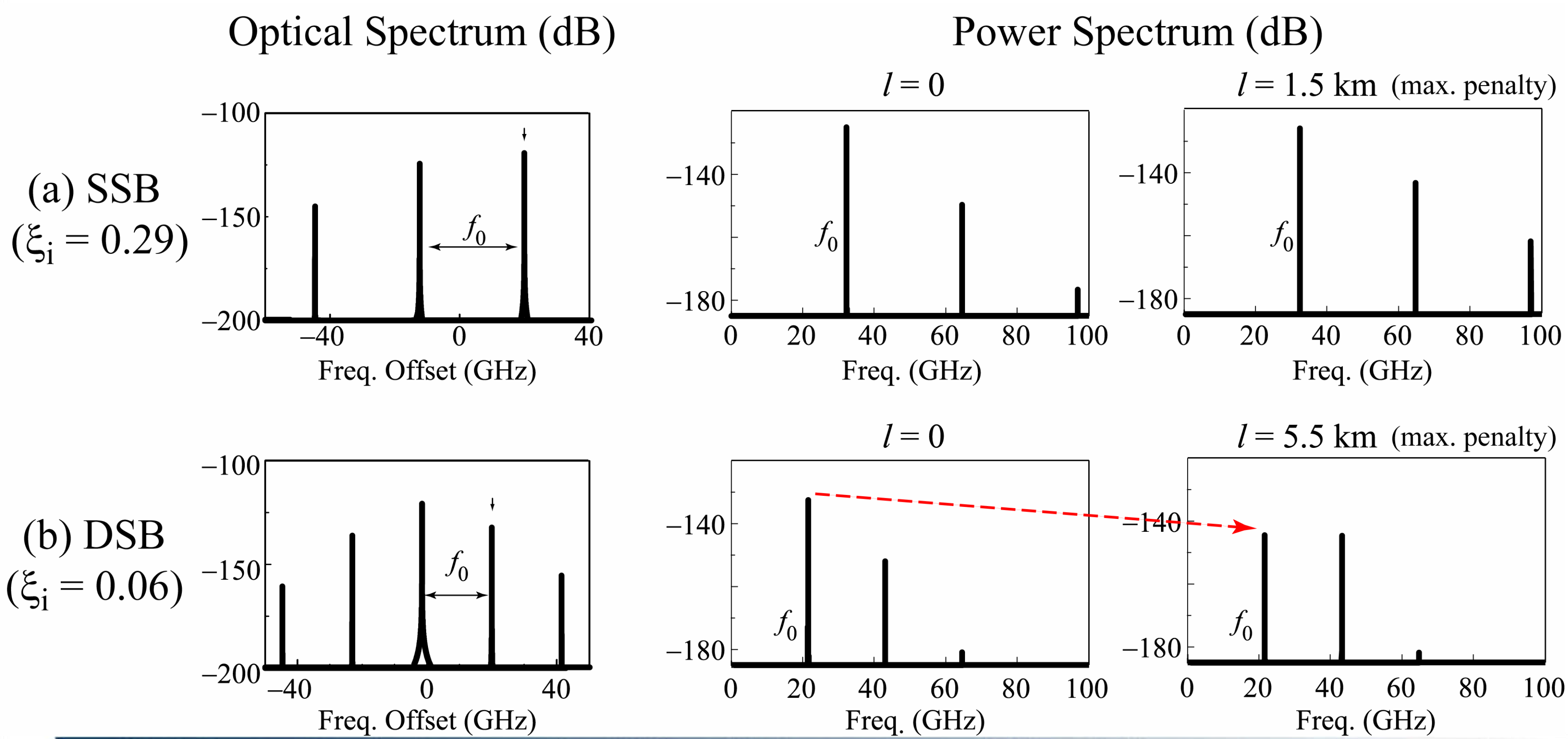


Apply the P1 state as an SSB RoF source

Immunity to RF Power Penalty

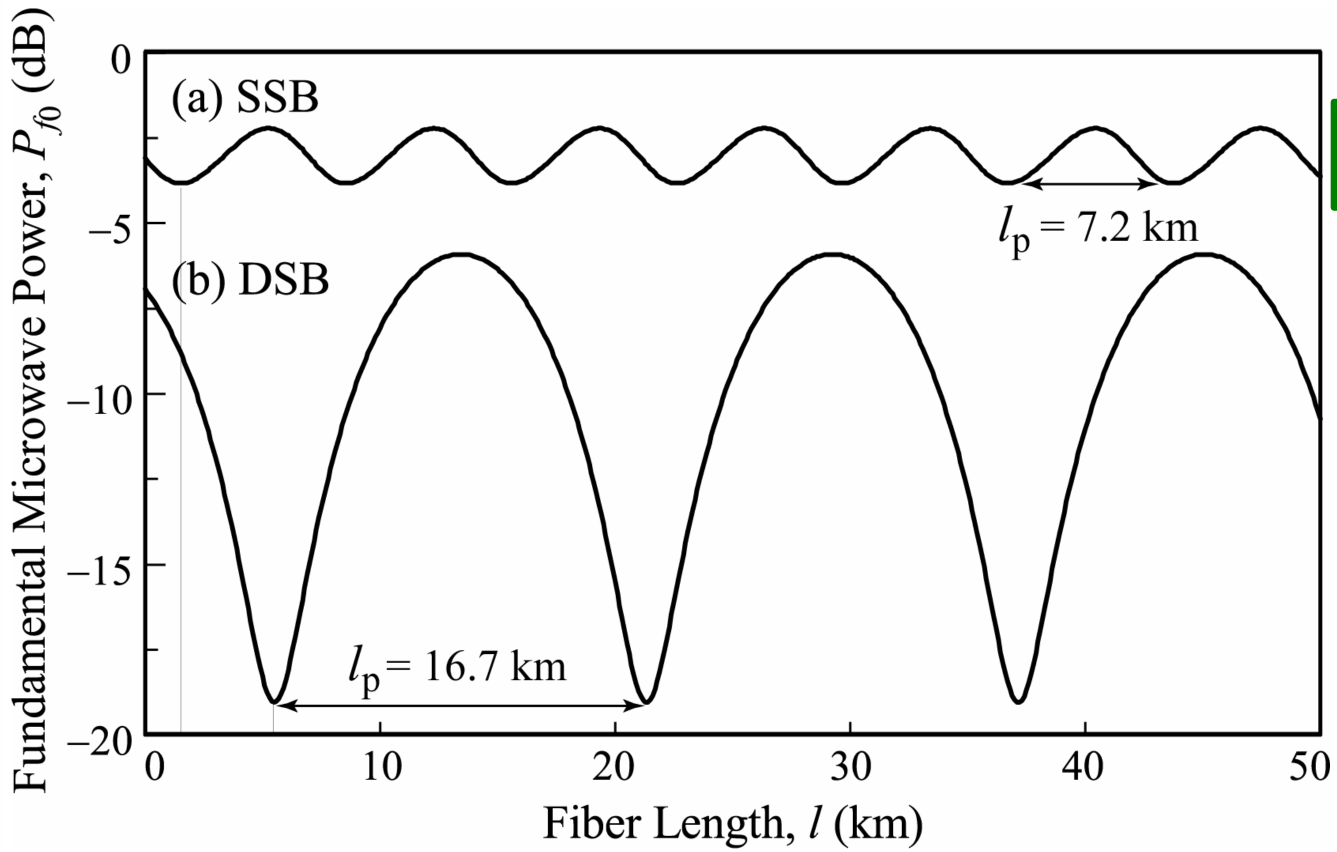
SSB can be generated





Power Penalty

- Periodic drop of RF power: $l_p = c / [f_0^2 \lambda^2 D_\lambda]$

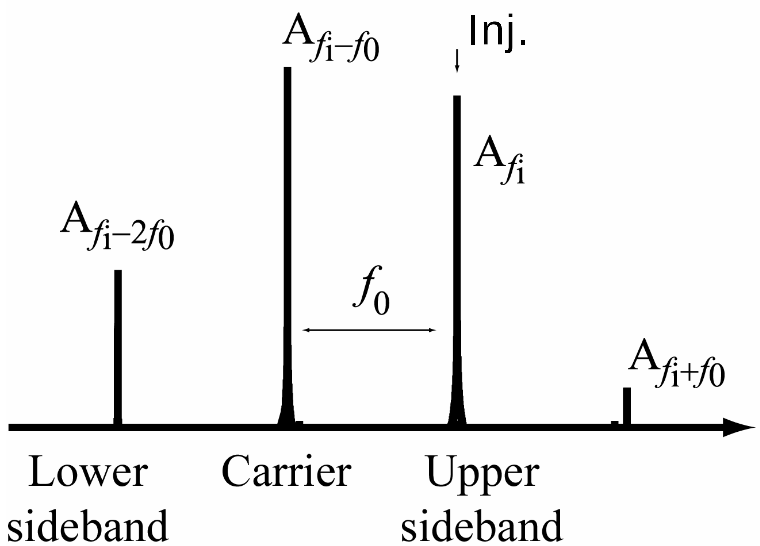


<2 dB variation (SSB)

16 dB variation (DSB)

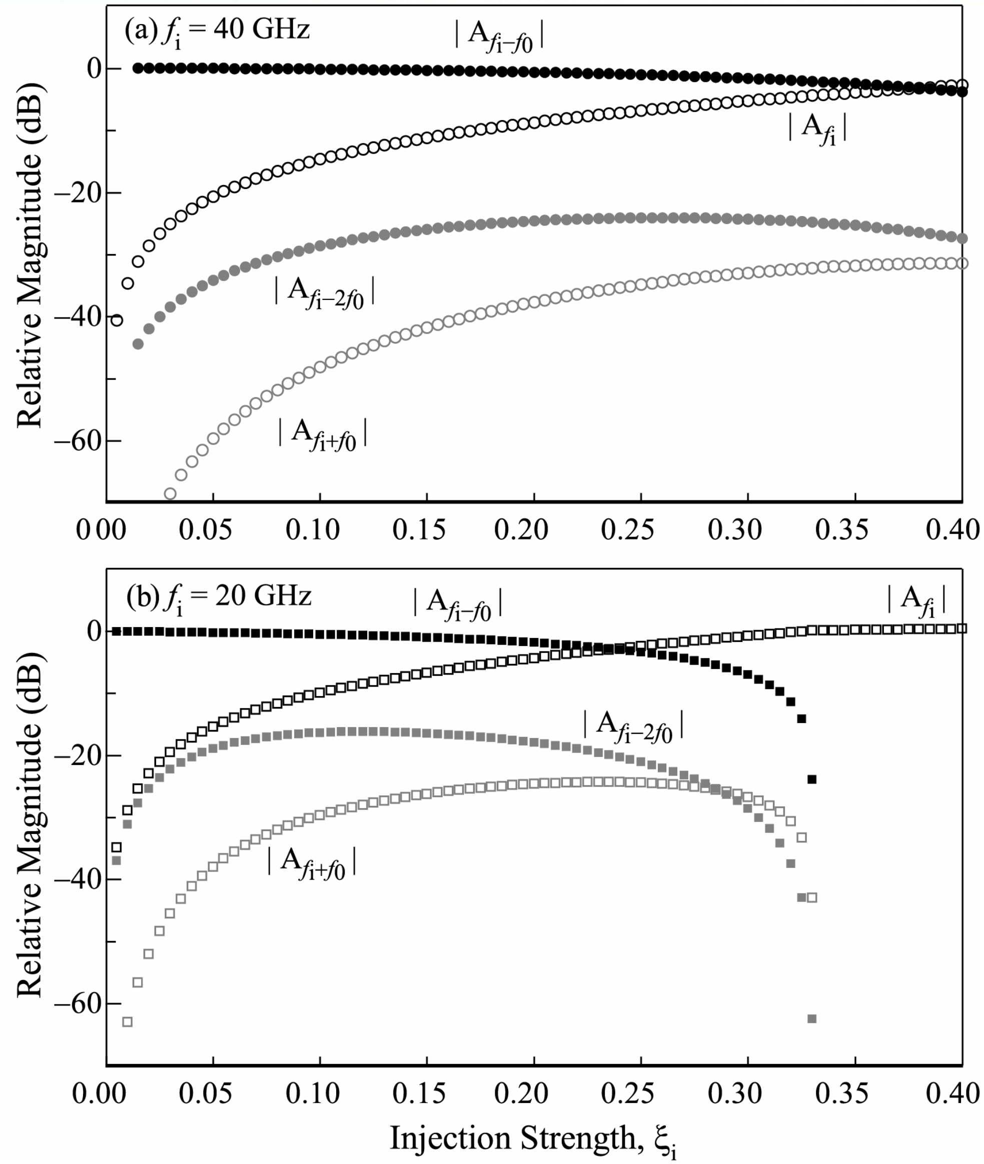
SSB Property of P1

Optical Spectrum

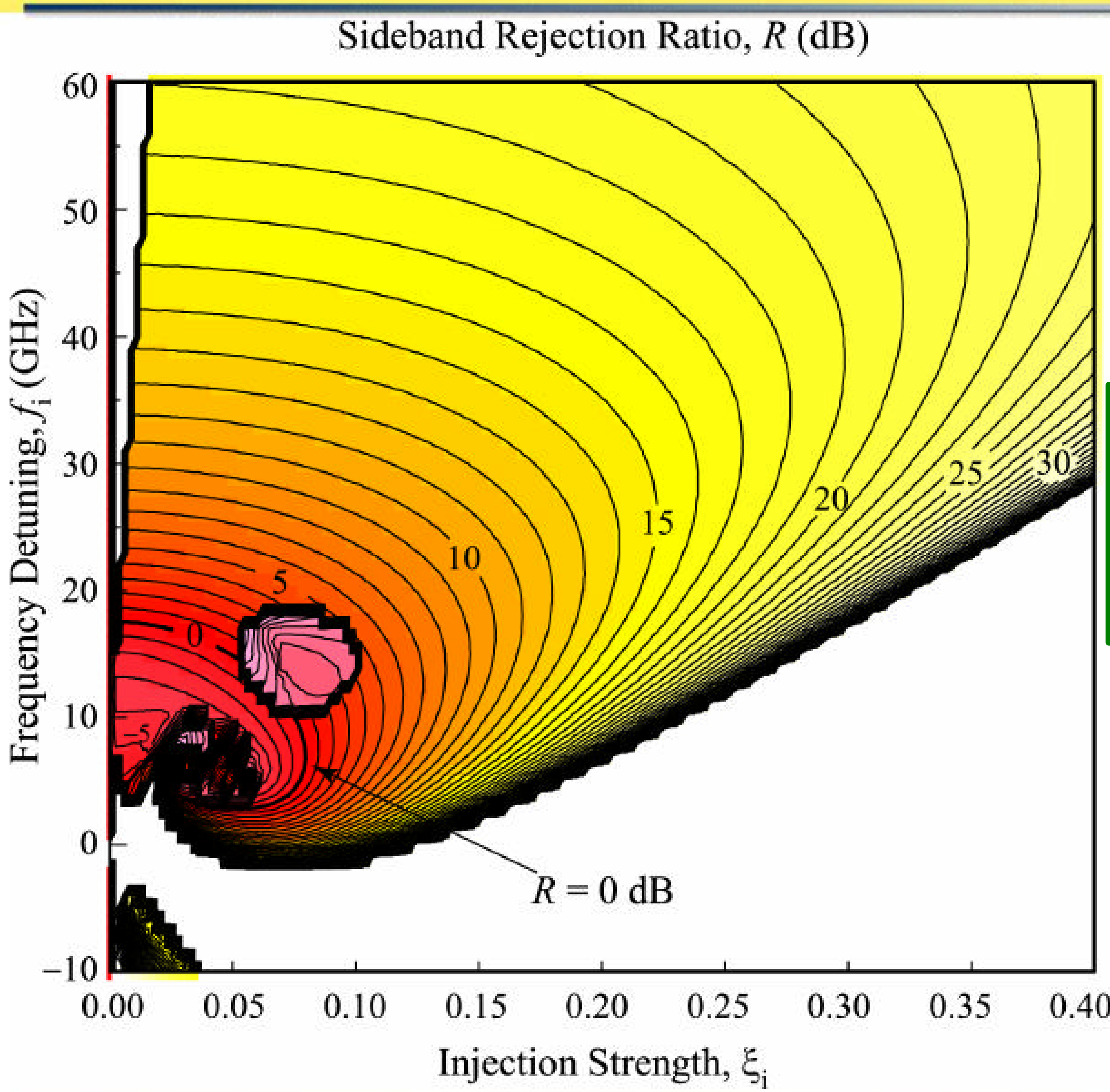


- Strongest lines:
  $(f_i - f_0)$, f_i, $(f_i - 2f_0)$

- Sideband rejection:
  $R = A_{fi} / A_{fi-2f0}$

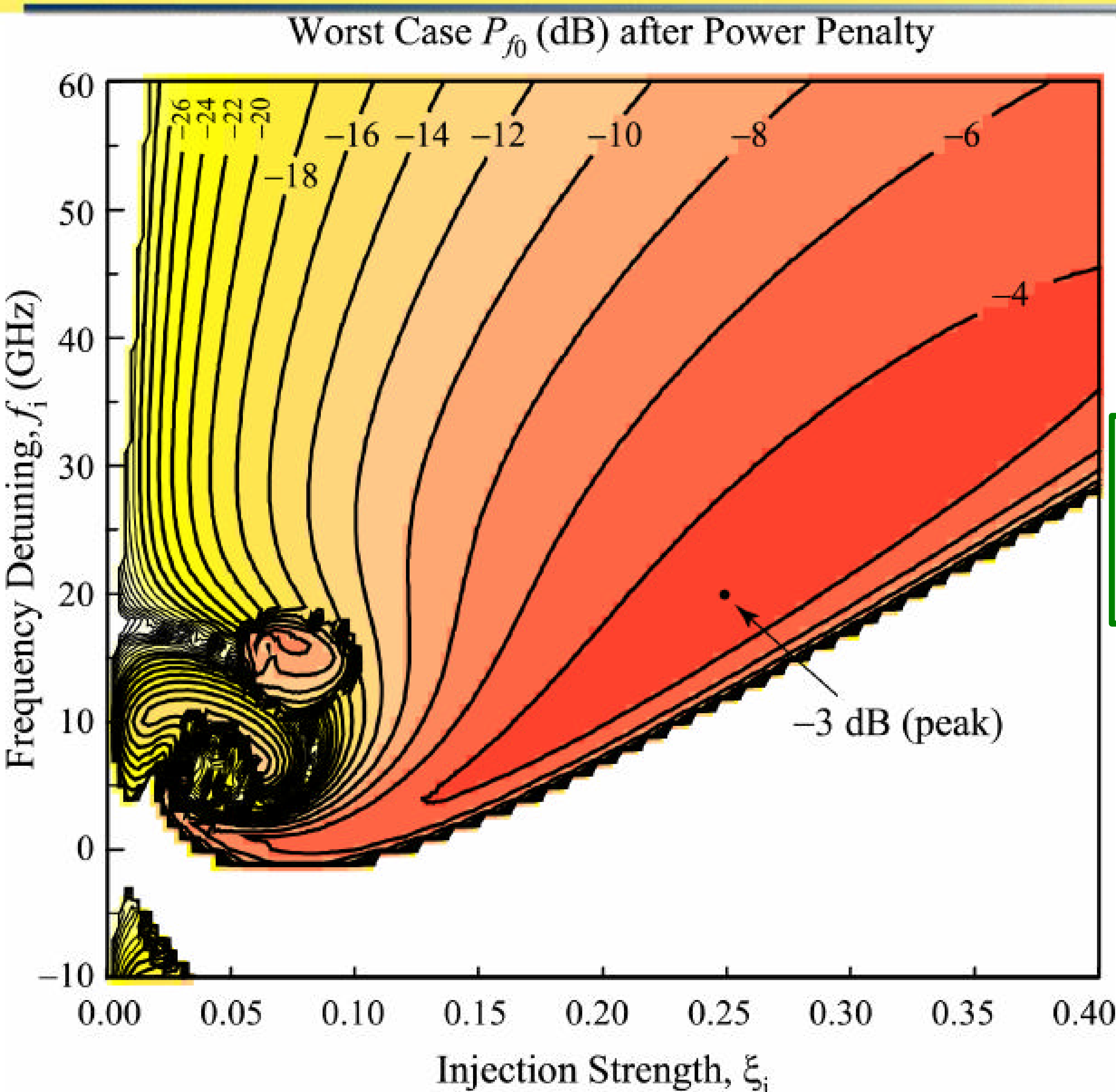


Sideband Rejection Ratio



The P1 state approaches ideal SSB when operated near the Hopf bifurcation line.

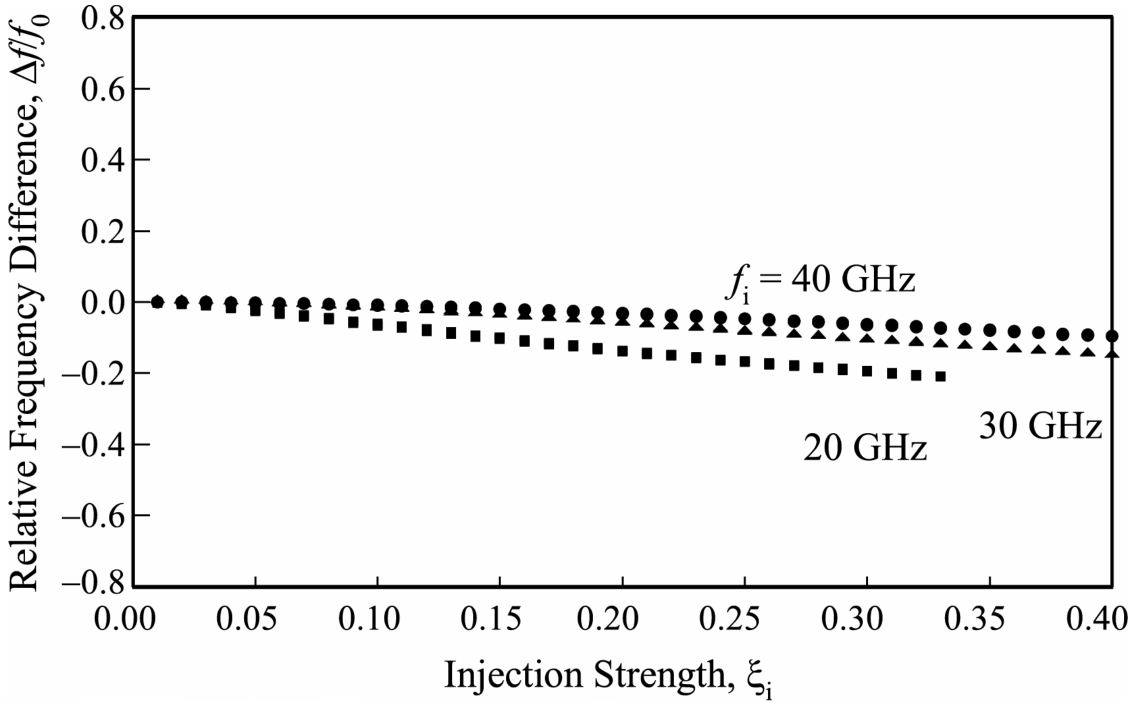
Worst Case Power after Fiber

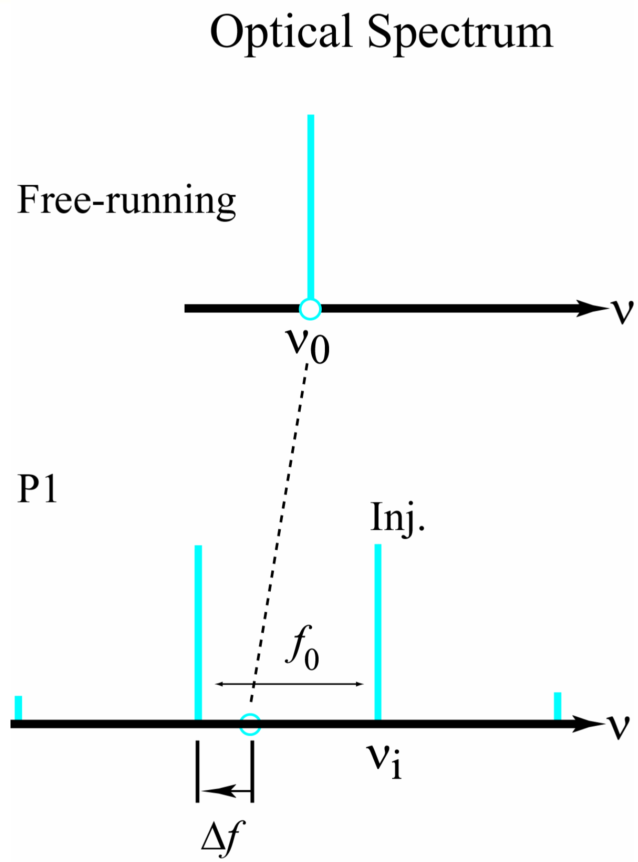


Best performance when operated slightly above the Hopf bifurcation line.

Mechanism for SSB: Cavity Effect

- As injection increases:
  - Laser goes from free-running to P1:
    - Gain decreases
    - Index increases
    - Effective cavity length increases
    - Cavity undergoes red-shifting

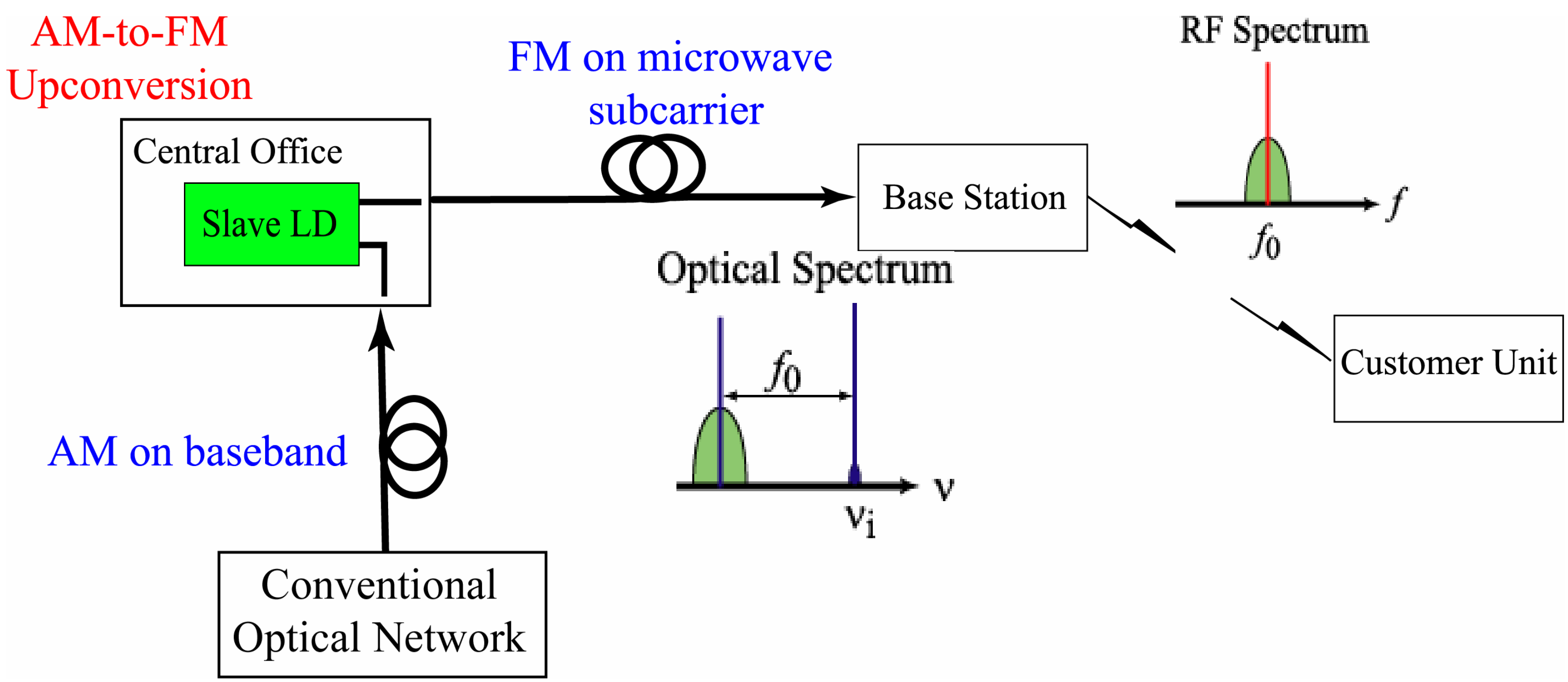




The sideband just below the injection is nearest to cavity (most enhanced).

Application 3: AM-to-FM Upconversion

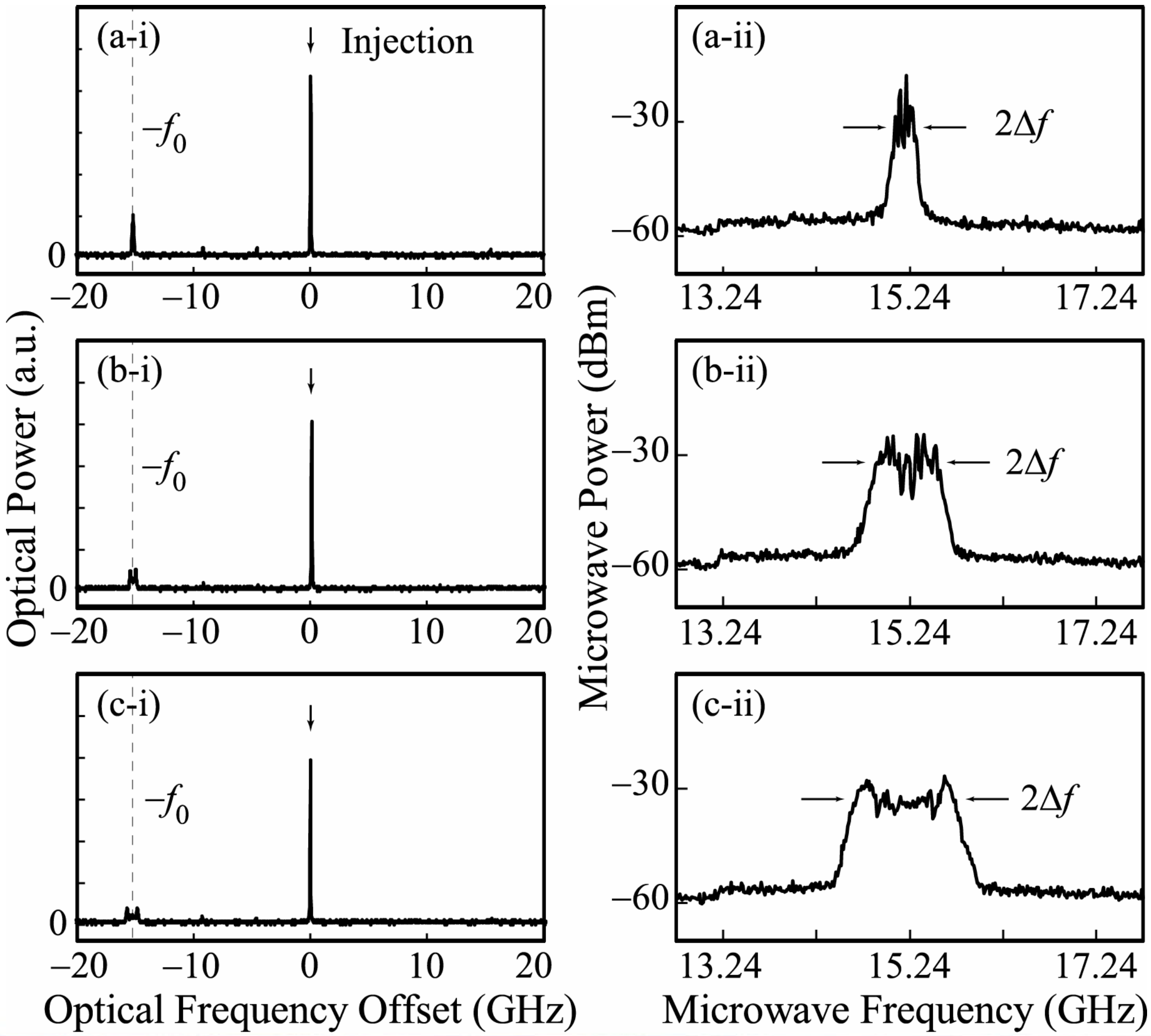
- AM-to-FM upconversion is needed at the interface between a conventional optical network and an RoF system.



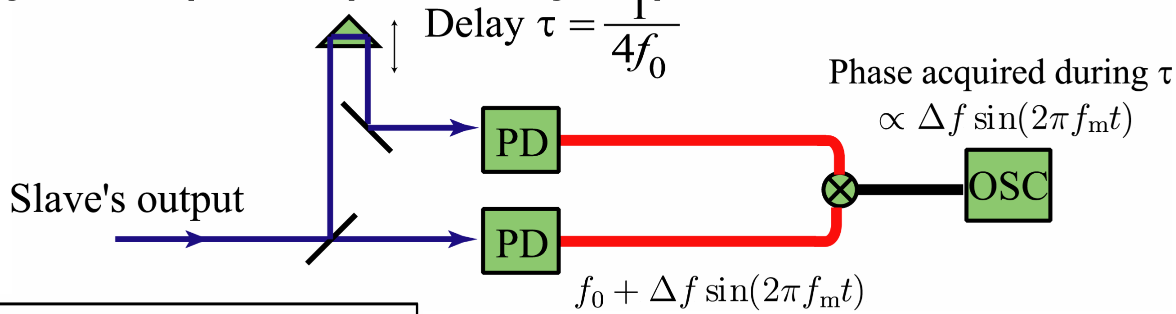
- The P1 generated microwave f_0 can be modulated by a time-varying injection:
  - Optical wave carries a microwave subcarrier that, in turn, carries data

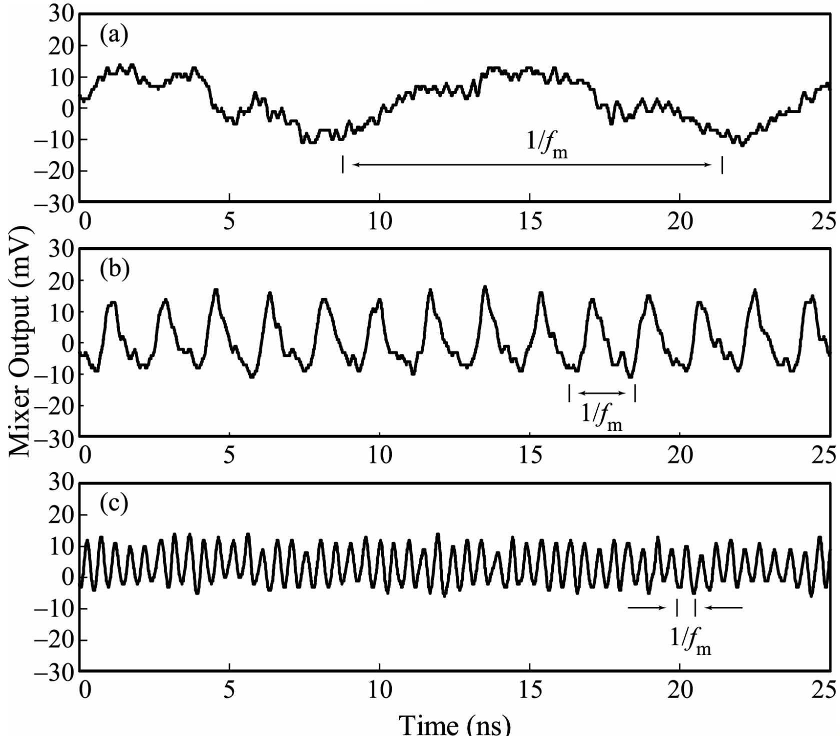
Modulation Behavior of P1

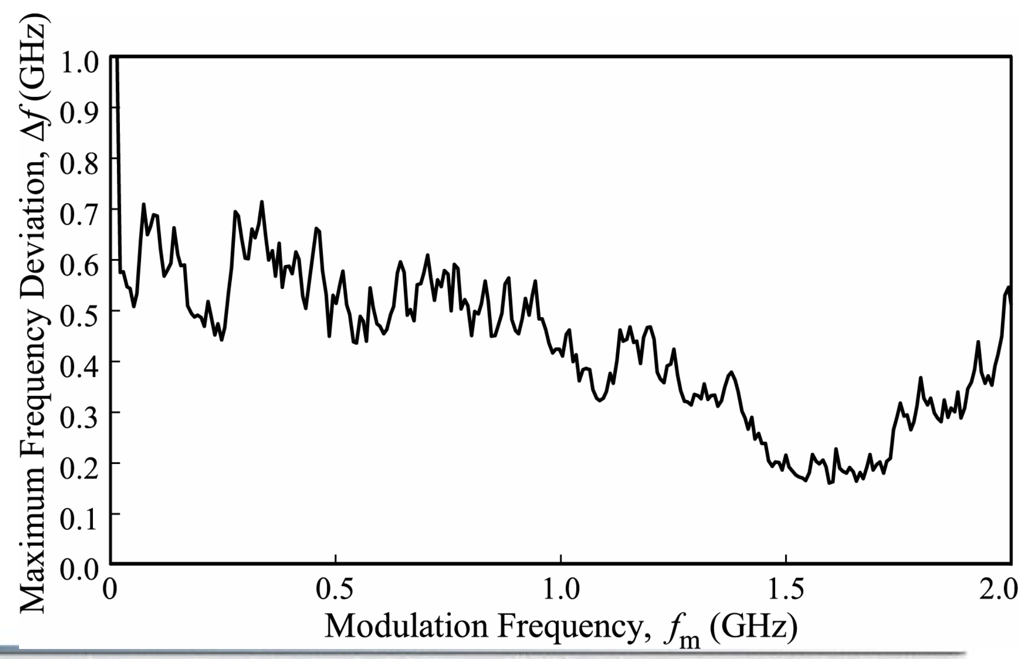
- FM frequency deviation Δf increases with injection modulation strength
  - 0.05
  - 0.08
  - 0.10



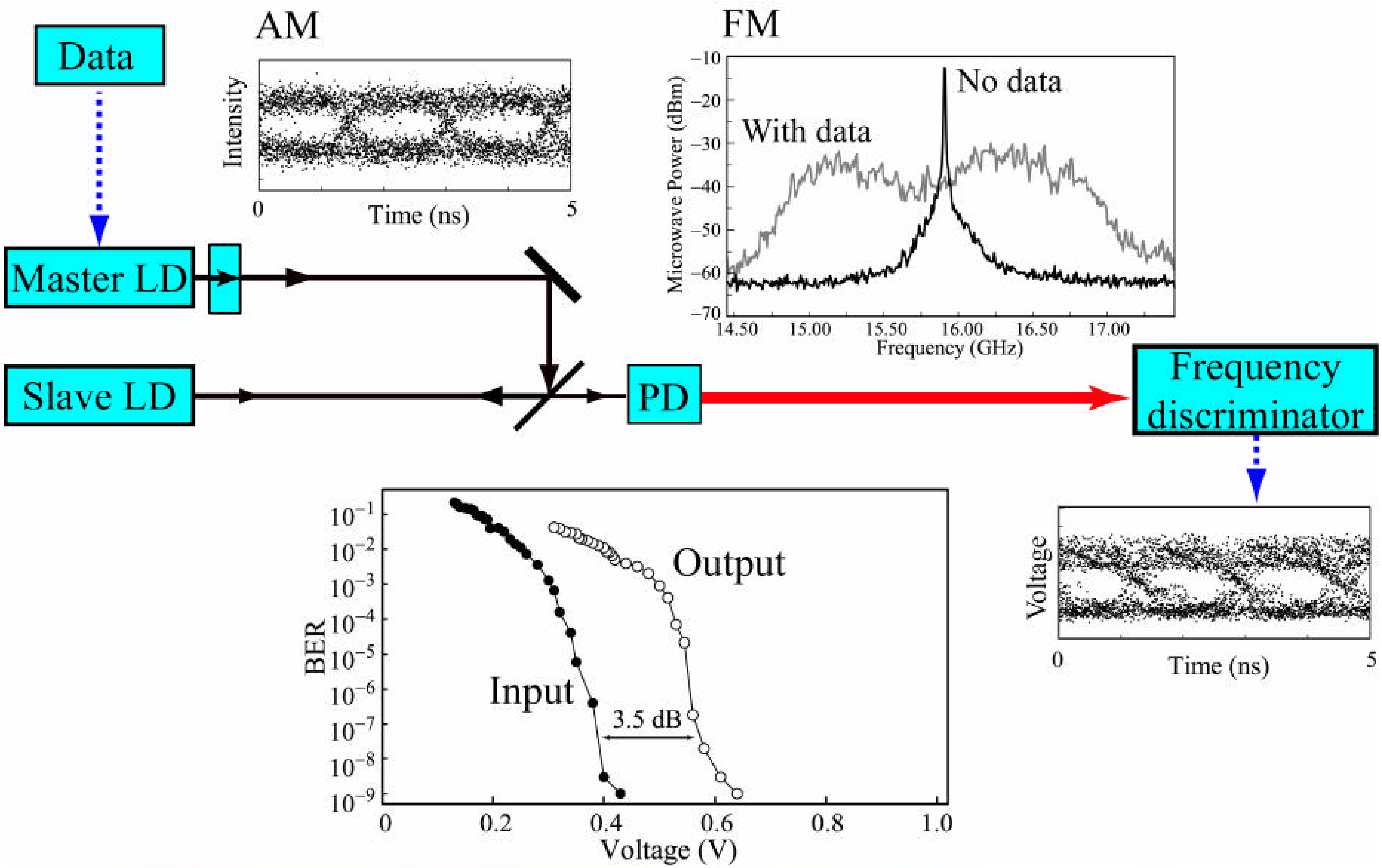
- Instantaneous frequency is measured by mixing the microwave with its delayed replica (homodyne)







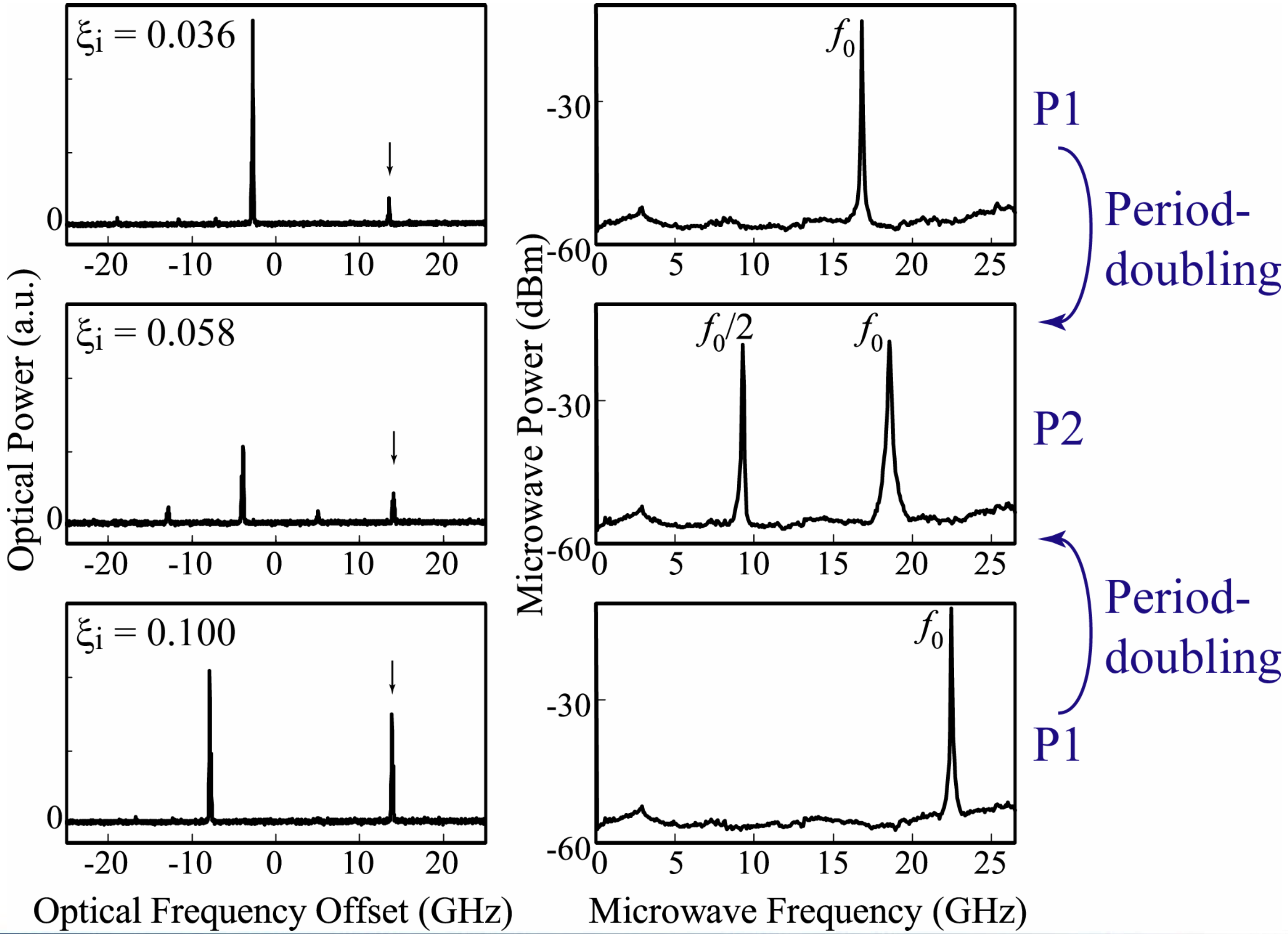
BER Measurements



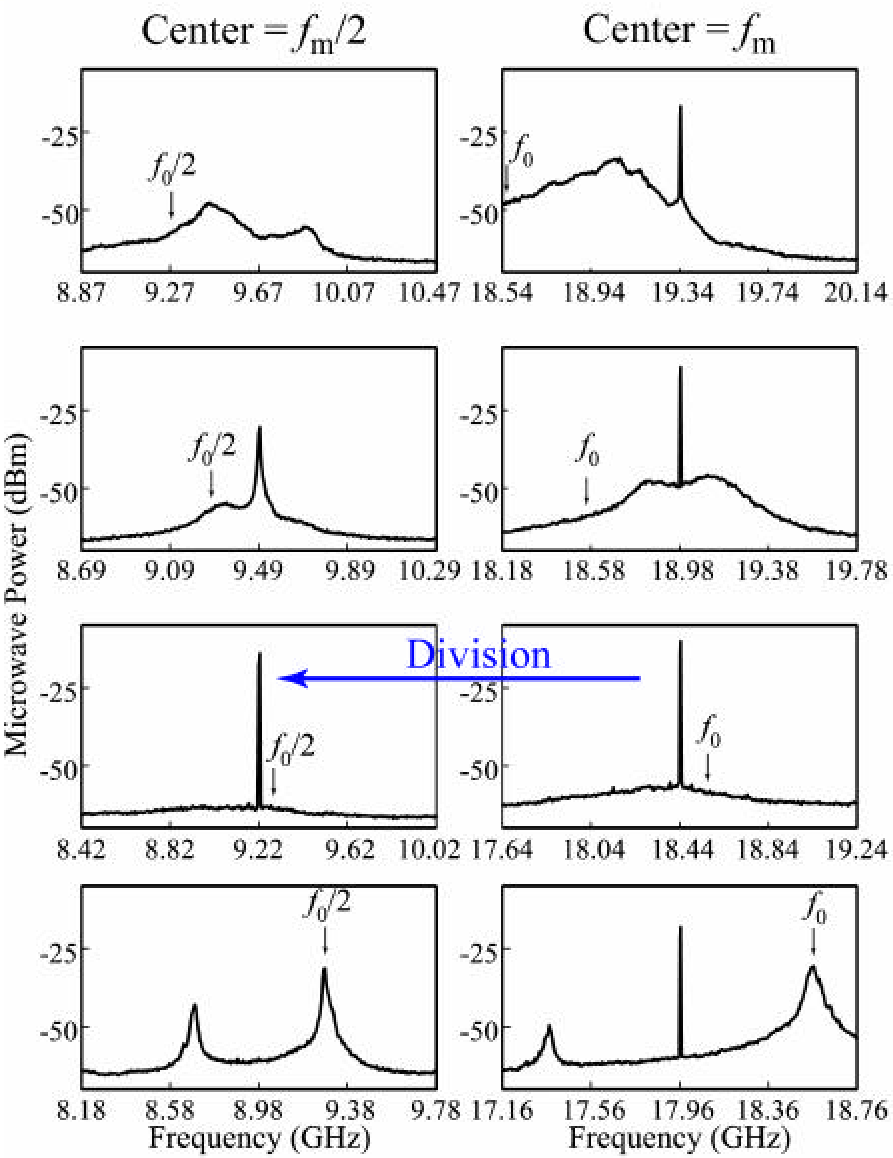
Optical Injection Period-Two State

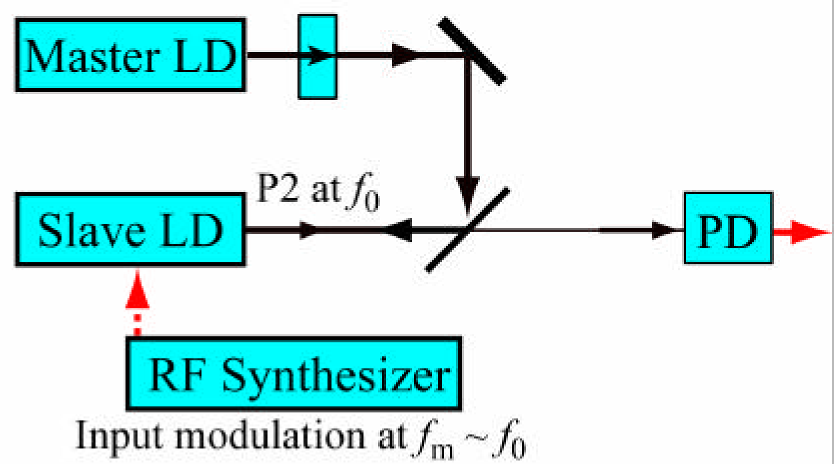
P2 Spectrum

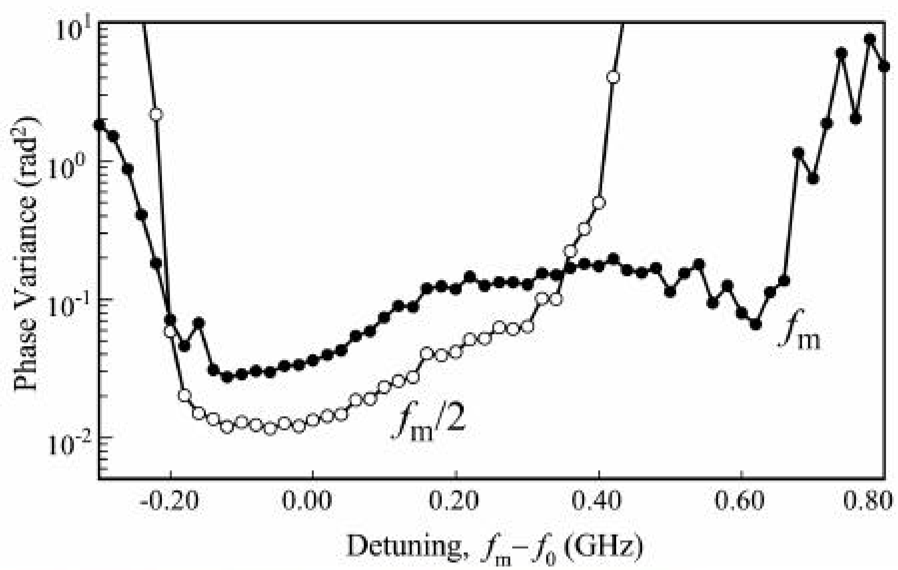
- P2 state is obtained using the same optical injection system under different injection conditions.



Application: Frequency Division

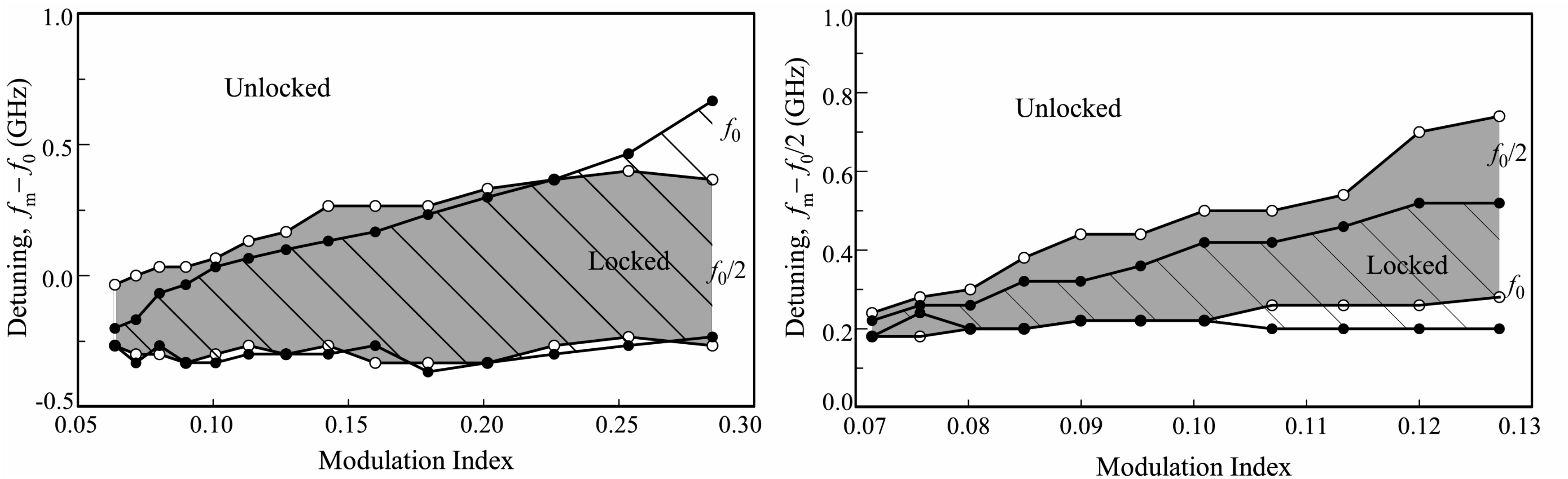






Locking Range

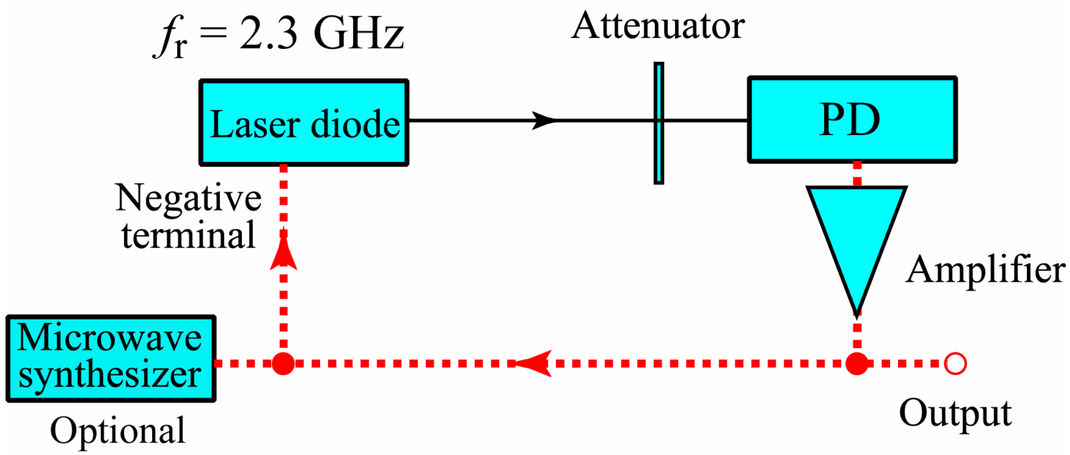
- Locking range: phase noise less than a limit (0.5 rad^2)

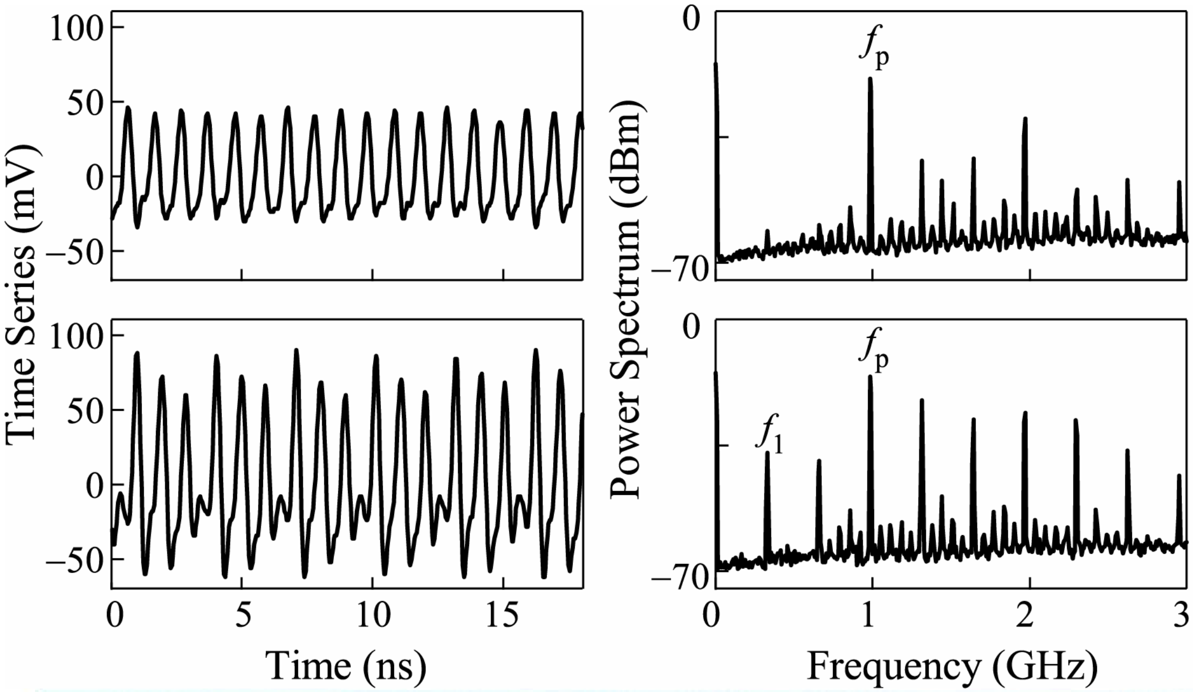


- Modulation at either the fundamental or the subharmonic locks both of the frequencies:
  - If modulated at the fundamental, P2 state acts as a <u>frequency divider</u>
  - If modulated at the fundamental, P2 state acts as a <u>frequency multiplier</u>

Optoelectronic Feedback Frequency-Locking State

Optoelectronic Feedback





Feedback strength:

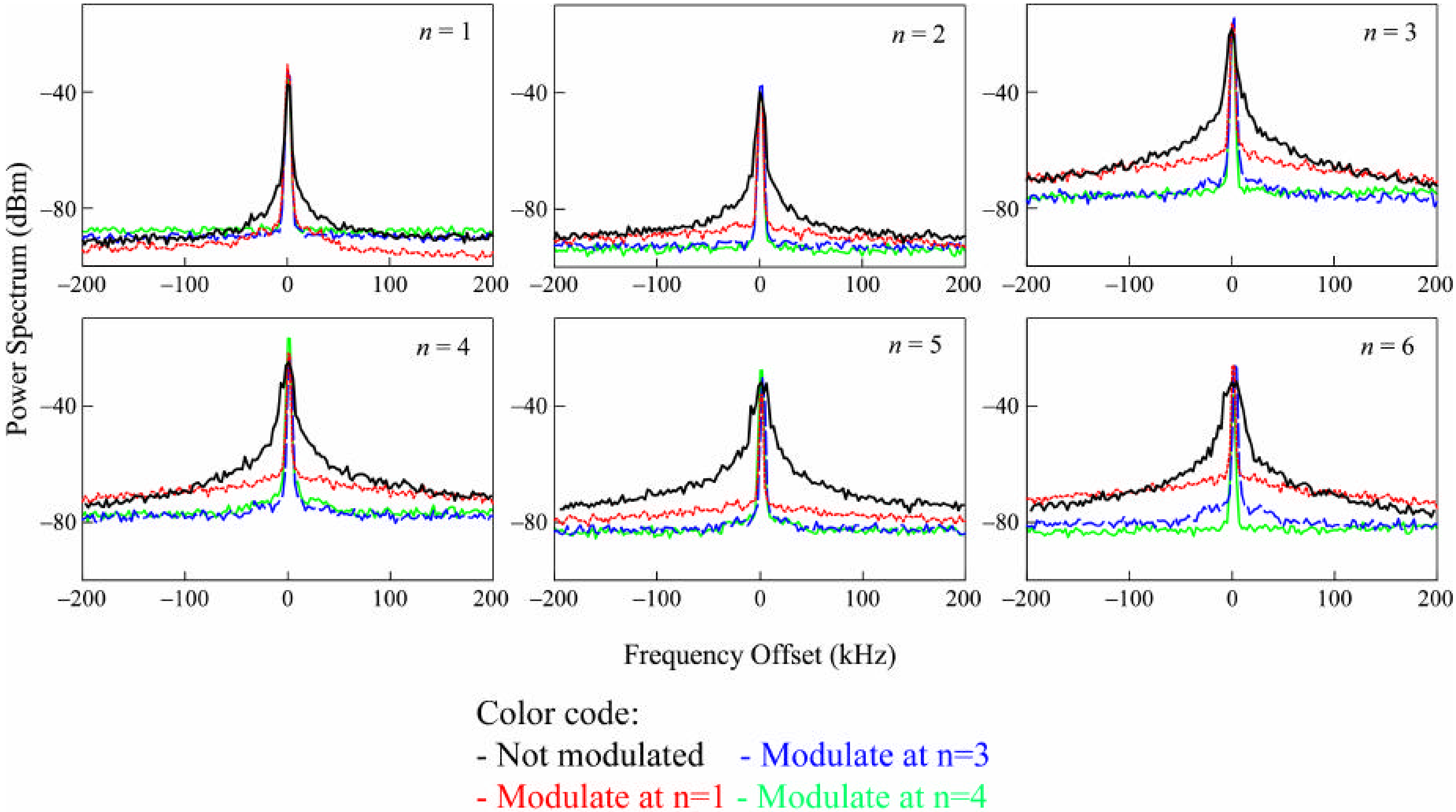
−0.22 (regular pulsing)

−0.23 (frequency-locking)

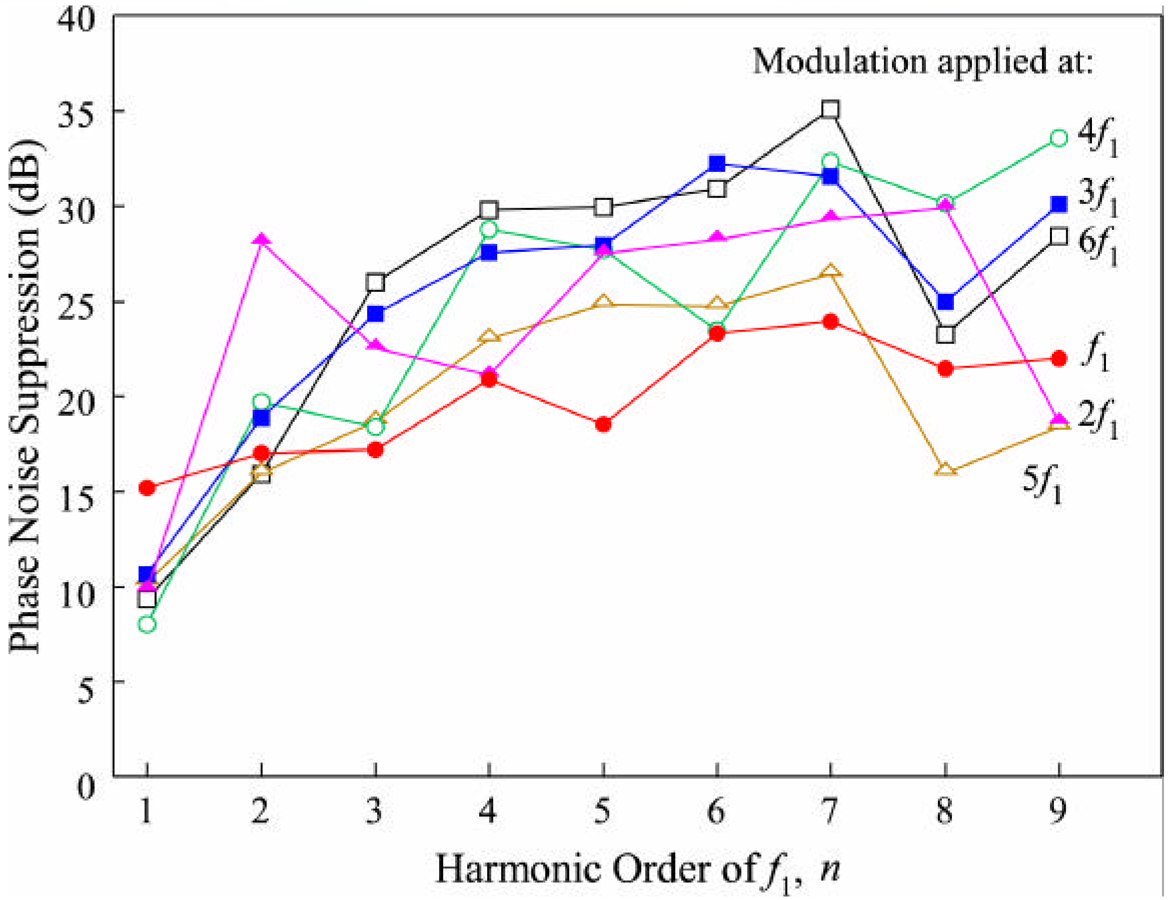
f_1:f_p = 5:15

Microwave Injection-Locking

- All comb frequency components (nf_l) can be locked by microwave injection at an arbitrary component.



Phase Noise Suppression



- Laser nonlinear dynamics generates the frequency comb; microwave injection stably locks the comb.
- The resulting pulses are similar to that obtained by modelocking.

Summary

- Nonlinear dynamics of semiconductor lasers are considered for many photonic microwave applications
- Optical injection P1 oscillation
  - Obtained from Hopf bifurcation
  - Generates a widely tunable photonic microwave signal
  - Doppler lidar, radio-over-fiber transmission and AM-to-FM conversion
- Optical injection P2 oscillation
  - Obtained from period-doubling of P1
  - Microwave frequency division and multiplication
- Optoelectronic feedback frequency-locking
  - Generates stable microwave frequency comb

Thank You!!

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